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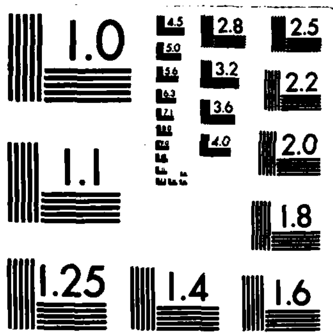

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PHYSICAL OCEANOGRAPHY PROGRAM

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PROGRAM SCIENCE ABSTRACTS

1 APRIL 1985

OFFICE OF NAVAL RESEARCH

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This report presents a summary of work sponsored by the Physical Oceanography Program (Code 422PO), Office of Naval Research, Environmental Sciences Directorate, covering the FY84 period. It includes brief descriptions of research for about 100 physical oceanography projects.

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FORWARD

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This report, published annually, is a compilation of abstracts submitted by the principal investigators. The abstracts describe work supported by Code 422PO during FY84.

The report is intended to communicate the diversity and scope of the physical oceanography effort. We encourage comments concerning the research, or this publication. We also encourage contacts directly with the scientists themselves, and have provided addresses and phone numbers for that purpose. Programmatic questions should be addressed to the 422PO staff.

Keywords: Naval research.

Acknowledgements are due to the scientists for prompt and informative abstracts, and to Kathleen Dillard for typing and Maurice Jefferson for assembly.

INTRODUCTION

The Office of Naval Research supports a broadly based oceanography effort. This volume documents the physical oceanographic aspects, which are presented as abstracts submitted by the principal investigators. The purpose of this introduction is to provide a brief program overview, and to relate a few major components to one another.

(to p i)

The physical oceanography program addresses ocean phenomena on scales from ocean basins to turbulence. A division into three areas is made to distinguish the principal efforts: General Circulation, Mesoscale Variability, and Small Scale Variability. We emphasize that this separation, while acknowledged by most oceanographers, has no rigid boundaries. In fact, much of the recent excitement comes from the fascinating and complex range of scale interactions present in the ocean. For didactic purposes, however, we retain the three components.

General circulation or large scale elements in the program focus on the nearly steady state (time scales of years) and large dimensions (greater than a few hundred km.). Topics of interest include the major gyres, recirculation, western and eastern boundary currents, water masses, and recently, thermocline and ventilation processes. Work is largely observational, but components in modeling and theory are well integrated. On the locator map (p. 116) numbers refer to field efforts according to the key, p. 115. The index on page iv lists the components of the large scale effort.

Mesoscale variability addresses oceanic phenomena of time scales of order of weeks to months, and space scales from tens to a few hundred km. These phenomena include eddies and fronts, and Rossby waves. Program emphasis is on the understanding of the causes of the phenomena, their effect on both larger and smaller scales, and their evolution in space and time. Modeling and theoretical efforts here are quite diverse, since the features involve subtle dynamical balances. Observational programs are underway and are planned for the future in the newly funded Accelerated Research Initiative (ARI) Synoptic Ocean Prediction. This ARI seeks to obtain real time data for nowcasts and forecasts of the mesoscale eddy fields

The small scale program embraces those phenomena at time scales typically less than 1 day and of limited spatial extent in the horizontal and vertical. In the program, a series of focused at sea experiments have been mounted recently, since observational limitations at these scales are severe. The small scale program is funded by ARI's in Upper Ocean Variability, and Air-Sea Interaction. Future funds are available in a Fine Scale Variability ARI. The recent experiments include LOTUS, MILDEX and AIWEX and plans for FASINEX are well advanced.

Two additional ARI's provide support for Remote Sensing and Southern Studies. This latter ARI supported recent field programs in the Brazil-Falkland, Agulhas, and Madagascar regions.

Finally, instrumentation development, an indispensable component, is listed on page vii.

This overview highlights but a few of the many research topics in the program. The abstracts that follow provide a more balanced view, but as abstracts, merely whet the appetite. We hope this compilation will encourage a closer rapport among the scientists represented here, but in addition, among the members of the community at large.

<u>LARGE SCALE</u>

MESOSCALE

SMALL SCALE

INSTRUMENTS/TECHNIQUES

HYDRODYNAMICS OF STRATIFIED FLUID AND INTERNAL WAVE INTERACTION WITH MESOSCALE FLOW

Principal Investigator: Henry D. I. Abarbanel

This research is concerned with the mechanisms of transfer of physical properties such as action and energy between oceanographic flows on widely differing spatial and temporal scales. In particular, the generation of internal waves by the shears in mesoscale flows is the central subject. This transfer, as with many transports in fluid situations is much more rapid and efficient when the flows are turbulent. Our research, then, has concentrated on making models of the mesoscale and internal wave fields and discovering when they are stable and laminar, and thus very inefficient in transport, and when they are unstable and turbulent or chaotic, and then much more capable of this kind of transport.

Our attention during the current year has been on the nonlinear stability of stratified shear flows. These represent the background or mesoscale flows which drive waves -- internal waves -- in the stratified medium. Our central result, published in *Physical Review Letters* in June, 1984 is a Richardson number criterion for the nonlinear stability of parallel shear flow in a stratified medium. This generalizes the results of Miles and Howard about the linear instability of such flows. Our result points to the very interesting range $1/4 < Ri < 1$, in which these flows are linearly stable but nonlinearly unstable. Since much of the observed oceanographic data lies in this regime, both laboratory and further oceanographic experiments are indicated.

The technique used in this analysis is the constrained energy principle of Arnol'd. We have extended this to the stratified or inhomogeneous fluid case and are now, in collaboration with D. Holm of Los Alamos and J. Marsden of Berkeley, further investigating the implications for the method and the ocean physics of an additional conserved quantity beyond potential vorticity for internal wave flows and mesoscale fields not involving changes in specific entropy.

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LAURENCE ARMI

OCEAN MIXING PROCESSES

Frontal structures have distributions and scales given primarily by the strain field of the large-scale flow, the coherent features of which are distinctive signatures clearly observable in satellite infra-red scanner images. We have found that surface and subsurface gradients and structure of the temperature and salinity field depend strongly on position within these large-scale structures. This is a continuing investigation; satellite observations determining the in-situ sampling strategy. Although the California coast was chosen because of operational simplicity, we believe that only a limited number of coherent structures exist in oceans and that a study of the type begun here will be appliable to other areas as well.

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JOHN M. BANE, JR.

OBSERVATIONS OF THE CURRENT STRUCTURE AND ENERGETICS OF GULF STREAM FLUCTUATIONS DOWNSTREAM OF CAPE HATTERAS

The Gulf Stream leaves the continental margin northeast of Cape Hatteras, NC, and flows into deeper water where meanders propagate and grow downstream. Earlier measurements have focused on the region 100-400 km downstream of Cape Hatteras, where an array of inverted echo sounders (IES) and deep current meters have been highly successful in monitoring the Stream's path and deep current fluctuations. A comprehensive study comprised of an extended IES array, an array of current meter moorings which extend up to 500 m from the surface, and AXBT surveys with closely-spaced stations was conducted during the 1 year period which began in January, 1984. The successful year-long deployment of our five "tall" current meter moorings has demonstrated the feasibility of making direct current measurements in this portion of the Stream over a long time period. These measurements were made in order to better determine the structure of the Stream, the energetics of its fluctuations, and to test theoretical predictions of characteristic signatures of barotropic and baroclinic instability. The current meter and AXBT portions of the research program have been supported by ONR, while the IES array was principally supported through a NSF grant to D. R. Watts of the University of Rhode Island.

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RUSS E. DAVIS

UPPER OCEAN DYNAMICS

During 1984, effort was directed toward several projects involving observations and analysis of upper ocean velocity fields.

1) During MILDEX, upper ocean currents were observed using a shipboard Acoustic Doppler Current Profiler and inexpensive current-following drifters. The velocity field was dominated by complex shears of shorter scale than usually found in wind-driven regimes. Work is underway to join these observations with those of other MILDEX participants.

2) In cooperation with Webb Research, efforts were underway to exploit pop-up neutrally buoyant floats in the observation of the general circulation. A General Circulsion Drifter is being developed which repetitativly cycles to the surface, transmits signals for ARGOS location, and then returns to depth for further current-following. Efforts to exploit direct chemical to mechanical energy conversion for ascent cycling have been abandoned and a battery-powered hydraulic pump approach adopted. The prototype will be field tested in the spring of 1985 and long-term engineering tests begun before year end. To help in learning how best to utilize these infrequently located drifters, an eddy revolving numerical model is being prepared to simulate float motion. One of the analysis methods to be examined is objective function fitting (Davis, _JGR_, 1985).

3) Preparatory to participation in the Frontal Air-Sea Interaction, a three-dimensional frontal/mixed layer model is under development. This was first applied to a coastal upwelling circumstance where a front is formed within the mixed layer as it is swept offshore by Ekman flow. The scales of the front are dependent on vertical mixing within the layer and there are significant differences between mixing parameterizations (shear instability _vs._ wind shirring).

4) During the remainder of the present contract period effort will be directed to demonstrating the performance of a Row-Deines self-contained Acoustic Doppler Current Profiler from a surface mooring. This is necessary preparation for the Ocean Storms experiment where we intend to document the response of the upper ocean to wind forcing and to see how that response changes as the mixed-layer deepens during the fall/winter transition.

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Atmospheric Forcing on Ocean-Atmosphere Boundary-Layer Processes

This effort includes model formulation/evaluation and observational studies on the coupling between structures and processes in the adjacent oceanic and atmospheric layers. The formulation/evaluation tasks examine predicted evolutions in the oceanic and atmospheric boundary layers obtained from bulk models. Observations were made of atmospheric structure and forcing during MILDEX-83. Observations are being planned in the Frontal Air-Sea Interaction Experiment (FASINEX) in February and March 1986.

The objective is to characterize local air-sea interaction in terms of the coupled changes and equilibrium states within adjacent oceanic and atmospheric boundary layers. The characterization is based on measurements and computational resources available to a ship and is for predictions of both mixed layers for periods of 24 to 36 hours. The prediction would be for a point and exclude ocean and atmosphere advection effects.

The approach at present is to:

a. Evaluate a micro-computer based coupled intergrated marine atmospheric boundary (MABL) and ocean boundary layer (OBL) model. Evaluations include sensitivity analyses on exchange coefficients in the coupled MABL-OBL model with existing (MILDEX,STREX) and planned (FASINEX) data sets satisfying one dimensional constraints.

b. Obtain description of coupled MABL features and ocean forcing from shipboard measurements in experiments when (FASINEX) horizontal gradients at surface are important.

The work is being performed in collaboration with OBL modeling efforts by Dr. R. W. Garwood and with participants in the MILDEX and FASINEX experiments.

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Eric A. D'Asaro

MEASUREMENT OF UPPER OCEAN RESPONSE TO MID-LATITUDE STORMS USING AIRCRAFT EXPENDABLE VELOCITY PROBES

This linked program of field experiments, analysis and computer modelling studies is aimed at determining how the upper ocean responds to strong storms in mid-latitudes. This problem has two major aspects: determining the structure of these storms on the relatively small scales (10's to 100's of km) important to the ocean, and determining how the ocean responds to this forcing.

The analysis of previous field experiments, particularly STREX, suggests that much of the velocity response of the ocean to storms can be described by linear internal wave theory, coupled with simple models of the mixed layer turbulence (D'Asaro, E., JPO 1984). Analysis has thus shifted to modelling the velocity fields that occur under realistic storms. Analysis of wind records from long term buoys indicate that atmospheric features with a scale of about 100 km, principally cold fronts and small lows, are the most important features in generating upper ocean velocities. Work in progress concentrates on using high resolution wind fields from SEASAT to model the two-dimensional response of the upper ocean.

A major field program to test these ideas is planned in fall 1987. Called OCEAN STORMS, it will simultaneously measure the atmospheric forcing and ocean response during periods of strong storms in the northeast Pacific. Several dozen investigators will use a variety of techniques including drifting buoys, moorings, and aircraft expendable instrumentation.

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Eric A. D'Asaro

ARCTIC INTERNAL WAVE MEASUREMENTS USING THE XCP

Measurements of internal wave velocities and temperatures in the Arctic are being made as part of AIWEX, the Arctic Internal Wave Experiment. Previous measurements in the Arctic suggest that the level of internal wave energy is significantly less than in mid-latitudes. AIWEX is aimed at determining why. Since internal waves are very much the same at most locations in the mid-latitude oceans, measurements in a place were they are different (i.e. the Arctic) may help us better understand their dynamics.

The AIWEX field experiment is planned for March and April, 1985 in the Beaufort Sea. This contract supports measurements using the Expendable Current Profiler (XCP) which measures velocity and temperature down to 1500m. XCP's will be used to survey the area around the central AIWEX camp with the goals of determining the intensity and vertical and horizontal scales of the internal waves and of surveying the mesoscale eddy field in the area.

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D.L. CUTCHIN and W.B. WHITE

OPERATION OF A SHIP-OF-OPPORTUNITY XBT DEPLOYMENT PROGRAM IN THE PACIFIC OCEAN

Since 1976 Scripps Institution of Oceanography, in cooperation with the NSF, ONR, NOAA, ORSTOM (Office de la Recherche Scientifique and Technique Outre Mer) and FNOC, has been operating a volunteer observing ship (ships of opportunity) XBT program in the Pacific. At the present time the SIO/ORSTOM network consists of 30 vessels which deploy approximately 9000 XBT probes per year on 500 trans-Pacific sections.

Most of the resulting XBT temperature profiles are sent immediately to coastal radio stations and put on the GTS (Global Telecommunications System) for worldwide dissemination. They form a substantial part of the database used by the U.S. Navy and the U.S. National Weather Service to generate, in real-time, subsurface temperature maps for the Pacific. Data recorded onboard the vessels is processed at Scripps and regularly submitted to the NODC and FNOC. NODC accession numbers for collections of tropical Pacific sections are 83-00164 and 83-00165. Each of the mid-latitude sections are assigned a separate accession number. There are too many to list here. Independently Scripps has prepared, and is now in the process of distributing to interested parties, a large, research quality, XBT database which incorporates GTS bathymessages and on-ship recordings from the Pacific for the period 1979 through 1983. Access to these data can be obtained through NODC, FNOC or directly from Scripps by contacting D.L.Cutchin, S. Pazan, or W. White.

In addition to running the Pacific XBT network, Scripps' Volunteer Observing Ship program has, in cooperation with OSU (Oregon State University) and ORSTOM, developed very inexpensive and efficient computerized shipboard systems for the digitization, storage, and satellite transmission of XBT data. Several of these systems are now in regular use aboard volunteer observing ships.

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CHARLES S. COX

CARTESIAN DIVER OBSERVATIONS

The objectives of the observations are to study the evolution in time of shear in the thermocline, with especial emphasis on the appearance of turbulent events. The Cartesian Diver provides repeated profiles of velocity to depths of 300 m at round trip rate of one cycle per hour. Velocity shear is measured by the GEK method and evidence of turbulent motions is obtained by recording the spatial spectrum of conductivity fluctuations. Observations have been made in local waters, as part of the MILDEX program and independently in the deep waters offshore from central California. Preliminary results indicate the existence of a small number of localized turbulent events in 40 hours observation off the central California coast. A surprising feature of two events was their persistence between successive profiles. In both cases the vertical extent of the turbulent patches was more than 15 m. There has been no evidence of unusually intense shear in the water column preceding the appearance of the turbulent events. From these and earlier observations of water velocity it is possible to infer the direction of propagation of quasi-inertial wave motions. In two different observational series the directions were predominantly upward and downward respectively.

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October 1, 1983 - September 30, 1984

P. Cornillon/D. Evans

Mesoscale Surface Dynamics from the Gulf Stream to the Subtropical Convergence

Our current ONR funding is divided into two primary parts. The first deals with the Sargasso Sea immediately to the south of the Gulf Stream. As part of this effort we have documented the existence of large, apparently anticyclonic, eddies that detach from sharp meanders of the Gulf Stream (Cornillon and Evans, submitted to JGR.) We are currently completing a second manuscript with Weller, Price and Briscoe of WHOI, addressing diurnal heating events for which SST values are elevated significantly above the maximum value of approximately 1 C conventionally used in heat storage calculations for the mixed layer. We anticipate that our observations will have an important impact on such calculations. Finally, we are also involved with two other investigations of the area from which we anticipate publications. In one case we are preparing with Briscoe and Weller a satellite derived survey of mesoscale activity at the LOTUS morring over the two year deployment period. This involves a chronology of cold core ring passages, other eddy events and Gulf Stream meander activity that might have an impact on the mooring. This chronology is being integrated with the record of subinertial energy at the mooring. In the second case we are analyzing variablility, both in space and time, of the formation of 18 C water, an effort pursued by the ONR funded post-doc.

The second part of our funding deals with the Subtropical Convergence. Thus far the emphasis has been on cataloging the location of the fronts from 24 N to 32 N and from 63 W to 73 W. All fronts in over 2000 satellite passes of the area have been digitized. A statistical summary of these data and a comparison with XBT data will be presented at the FASINEX planning meeting of February 1985. The primary results of this work indicate: significant interannual variability in the location of the fronts; persistence in frontal positions for periods in excess of one month; some frontal activity at approximately 27 N in both years studied, and; maximum cloud cover in January (in excess of 50% of the time) with a strong north-south gradient in all months. We are currently assembling these results in a manuscript for submission this summer.

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Robert R. P. Chase

OCEANOGRAPHIC REMOTE SENSING APPLICATIONS

Many questions relating to meso- and large-scale, low-frequency ocean circulation might better be addressed with a more automated and integrated observing system. An integrated systems approach to observational oceanography would greatly expand the scope of ocean exploration beyond the bounds of existent, logistical and fiscal constraints. Consequently, a long-term goal includes developing a tripartite observing system (utilizing remote sensings, Eulerian, and Lagrangian measurements) capable of providing routine, low-cost measurements of various physical properties of the ocean such that, for example, statistical maps at several depths and frequency bands could be obtained.

Facilities provided under this contract form an integral component of a tripartite observing system. They consist of an appropriate selection of hardware and software capable of reducing both satellite and *in situ* data, integrating the data onto a four dimensional display of the recovered fields, and providing a convenient and powerful interactive tool for the joint analyses of these data.

The satellite remote sensing project is currently supporting research in the Agulhas, East China Sea, California Current, Africa, North Atlantic Basin, and Gulf Stream. Since data availability remains a significant problem and we anticipate a continued active program of Gulf Stream research, we intend to establish an active data base for the western North Atlantic.

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A SATELLITE-LINKED MOORED OCEANOGRAPHIC INSTRUMENT SYSTEM

The goal of this project is to develop a satellite-linked, moored oceanographic instrument system capable of supplying low-cost, long-term measurements of various physical properties of the ocean. We anticipate that this system will replace the existing standard intermediate mooring, providing significantly greater and simultaneous access to the data by any number of investigators located in geographically diverse areas and reducing the change per unit data record to a fraction of the present cost.

We have completed the conceptual design as well as the systems-level mechanical design. Currently, we are completing the electronic system design and proceeding with detailed mechanical and electronics designs. We anticipate broadening the scope of this project, enabling it to become the focus of all our "talking mooring" activities. It is likely that all telemetering moorings can utilize the vast majority of existing technology (i.e. generic subsurface mooring which communicates with instruments along the mooring line) with only the uppermost segment being changed to accommodate a specific research project (e.g. boundary current studies, upper ocean dynamics, low eddy kinetic energy regions).

We expect to construct the first prototype mooring in late 1986-early 1987 with an initial deployment during the summer of 1987.

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Harry Bryden

GULF STREAM OBSERVATIONS

As part of this ongoing research program, the first long time series current measurements extending from the bottom up into the thermocline of the fully developed Gulf Stream were successfully carried out from October 1982 to October 1983 at 37°37'N, 68°W. Year-long current meter records at 400, 700, 1000, 2000 and 4000 m depths provide the first unambiguous evidence that the Gulf Stream extends from top to bottom of the water column. By using the year-long current and temperature time series to profile across the Gulf Stream as it meanders past the mooring site, the width and transport of the Gulf Stream can be estimated for four individual events and an average profile of the vertical and cross-stream structure of the Gulf Stream can be determined.

Future analysis will focus on using the unique horizontal profiles of the Gulf Stream to determine the potential vorticity structure in the Gulf Stream and on investigating the dynamics of Gulf Stream meandering. It is also planned to develop a profiling system to measure currents in the upper waters of the Gulf Stream. The profiling system consists of a Doppler Acoustic Profiling Current Meter (DAPCM) embedded in a syntactic foam buoyancy sphere at the top of an intermediate mooring at about 400 m depth. The DAPCM will profile the velocity structure of the upper 400 m of the water column while conventional current meters will measure the deeper currents.

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SATELLITE REMOTE SENSING OF LARGE SCALE OCEAN TRANSIENTS

The long range objectives of this project include study of transient behavior of western boundary currents and associated eddy structures, frontal processes, and their response to atmospheric forcing as observed by satellite remote sensing techniques. Attainment of these objectives requires development of quantitative assimilation methods for satellite data on both large and small scales supported by suitable tools which yield timely access to calibrated, navigated satellite observations.

Efforts in the past year have focussed on obtaining a year long time series of high resolution NOAA AVHRR retrievals for the Brazil Current/Falklands (Malvinas) Confluence and setting up a global retrieval capability using a DOD furnished satellite receiving system. The confluence work, which started in August, 1984, is proceeding well. A cooperative endeavor with A. Gordon and D. Olson utilized near real time satellite data to guide the R/V Thomas Washington to selected mesoscale features for seeding with drifters during the October, 1984 cruise. Analyses of the limited retrieval set presently available finds large equatorward pulses of Falklands water offshore of a rather tight Brazil Current recirculation region. A longer term analysis (3 years) of seasonal SST frontal variability is now underway based on historical satellite data. The full multi-year data will be used for analyses of variability on monthly and longer scales.

Implementation of the DOD DOMSAT system is proceeding. We expect the receiver to be operational by mid-Summer, 1985.

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MELBOURNE G. BRISCOE
ROBERT A. WELLER

LONG-TERM UPPER OCEAN STUDY (LOTUS)

LOTUS was a two-year field effort to describe the local response of the ocean to a potpourri of atmospheric forcing in a variety of environmental situations (Briscoe, M., and R. Weller, *Dyn. Atm. Oc.*, 1984). The principal measurements were from an array of three subsurface moorings and one surface mooring carrying telemetering meteorological instrumentation as well as nearsurface current meters. The observations began in May 1982 in the Sargasso Sea halfway between Bermuda and Cape Hatteras, and ended in May 1984 with the final mooring recoveries and hydrographic surveys.

During this two-year proposal period the main work is to complete the field program (done), document the experiment and the data (in progress, partially completed), and initiate the scientific analyses (begun; see below). A part of the time is being spent assessing the performance of our surface mooring systems in terms of possible future work. One clear result of this study (still underway) is that the surface moorings performed extremely well, mostly because prior ONR support allowed us to refine the buoy and mooring technology before it was needed for the scientific field work; conversely, the new nearsurface current meters performed less well than hoped for, partly due to their being rushed into use before testing was completed.

Some principal scientific results to date include the first observations of the eddy kinetic energy profile from the surface to the bottom, which show a nearly constant eddy energy in the top 500 m (contrary to theoretical predictions of a surface intensification), and a seasonal cycle in the high-frequency internal wave energy such that the summer energy is lower, the winter energy higher; this is consistent with the wind stress variability at the site. The internal wave energy varies by about a factor of 10 from weakest to strongest, with short-term variations over a few weeks being nearly as large as the seasonal variations. Other ongoing studies include the response of the inertial field to the local winds, and the coherence structure of the low-frequency field.

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KENNETH H. BRINK

A LONG TERM STUDY OF THE OCEAN'S RESPONSE
TO FLUCTUATING WIND SOUTH OF BERMUDA

Two moorings were placed in the region south of Bermuda, bracketing a representative location of the subtropical convergence zone. A specific objective of the proposed experiment includes the investigation of the ocean's response, at both high and low frequencies, to atmospheric forcing. This project collaborates closely with the FASINEX effort.

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Dr. Douglas B. Boudra

Studies of the Agulhas Current System and its Role in the Global Ocean Circulation

In this research effort isopycnic coordinate numerical models are applied within a gradually more realistic framework to the wind-driven circulation of the South Atlantic-Indian Ocean. The objective is to contribute physical understanding of the medium to large scale characteristics of the circulation, such as the factors controlling exchange of fluid between the two basins. Both qualitative and quantitative comparison with observation of features of this scale are carried out to establish whether and to what degree the models simulate reality. The physics governing the model solutions may then be diagnosed with appropriate calculations from the fine space and time resolution model output.

Since this is one of the initial attempts to focus on the circulation of this region with a numerical/dynamical model, we began the project with very simple models--one-layer models, in fact--which used rectangular domains with the unique feature of an appendage from the northern boundary representing southern Africa, extending southward mid-way into a zonal, sinusoidal subtropical wind stress profile. The dynamics of the Agulhas current retroflection in this simple model were studied. It was found that inertial overshooting and the change in the vorticity balance as the current left the coast of South Africa controlled the exchange of water between the two basins. (De Ruijter, W. and D. Boudra, DSR, In Press, 1985).

Subsequent inclusion of stratification using a 3-layer representation further emphasized the importance of the vorticity balance. In the southward flowing Agulhas Current along the coast, the planetary vorticity advection is balanced by both relative vorticity advection and diffusion into the no-slip boundary. On leaving the coast, as the current does when it reaches the southern tip of Africa, the frictional dissipation is lost and now, to balance the planetary vorticity advection, most all of the fluid turns anticyclonically eastward, closing the subtropical Indian Ocean gyre. If the no-slip boundary condition is replaced by free-slip, the current, having no cyclonic vorticity on its west side, does not overshoot but makes the sharp turn into the Atlantic.

In recent experiments the South African coast (Agulhas Bank shelf break) has a more realistic 45° lat-lon tilt. Thus, planetary vorticity advection is much weaker and the overshooting current is less constrained to retroflect in order to maintain the vorticity balance. In this case, many aspects of the model retroflection, e.g., formation of Agulhas rings and leakage around South Africa along the coast, are apparently rather similar to those observed in the Fall '83 Agulhas Retroflection Cruise.

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RUSS E. DAVIS

SUPPORT OF SATELLITE OCEANOGRRAPHY EXPERIMENTS

The Scripps Satellite Oceanography Facility is run by SIO to support oceanography missions needing satellite imagery data such as provided by the AVHRR (Advanced Very High Resolution Radiometer) and CZCS (Coastal Zone Color Scanner) sensors on NOAA/NIMBUS series satellites. The facility routinely receives and archives data from the eastern North Pacific and prepares a "browse file" giving a low resolution description of the passes collected. The facility also provides image processing equipment and software for utilizing satellite and other imagery data. SSOF is available to educational and commercial users, trains new users, and accepts orders for specific products to be prepared by the staff.

During the past year SSOF has continued its collection and archival functions and presently collects on an 8-hour per day, 7-days per week basis. It has supported various ONR principal investigators and programs including:

1) Gautier/Pinkel/Davis (SIO). AVHRR imagery was collected for the MILDEX (Mixed Layer Dynamics Experiment) and transmitted to ships-at-sea in near-real time.

2) Winant/Guzu/Bray (SIO). AVHRR and CZCS imagery was collected and transmitted in near-real time to ships carrying out a field program in the Gulf of California.

3) Armi (SIO). AVHRR and CZCS collection and data relay to ship was a central element in an investigation of coastal fronts, eddies, and jets, off California.

4) Vastano (TAMU). SSOF provided archived data for an attempt to deduce surface dynamic height and flow from AVHRR images.

5) Whritner (SIO). AVHRR images were collected or transcribed from analog tapes collected elsewhere, processed and transmitted in support of Shuttle Mission 41G (the SIR-B oceanographer in space mission) and in support of Third Fleet operations in the SoCal and TransPac regions.

6) Mooers (NPG). Archived data was provided to support two OPTIMA cruises off the central California coast.

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Roland de Szoeke

UPPER OCEAN DYNAMICS

HEAT AND ENERGY BALANCES IN THE UPPER OCEAN DURING STREX

Subsurface temperature data and surface meteorological data were analysed for thermistor chain moorings near 50°N, 140°W during the Storm Transfer and Response Experiment (STREX). The upper ocean (to 90 m) heat and potential energy (PE) contents were monitored for an 18-day period and their changes compared to the sources and sinks of heat and turbulent kinetic energy (TKE). The one-dimensional balances of heat and TKE were unsuccessful. The heat content change, for example, averaged -180 W/m^2 while the net cooling at the surface estimated from bulk formulas for latent and sensible heat fluxes and radiation measurements averaged only 88 W/m^2. Thus, advection of heat, in either the vertical or horizontal, must play a major role in the heat budget of this area. The heat and PE contents exhibit some long-term trends but there are two marked events associated with storms on 15 and 27 November that account for most of the overall cooling and PE change.

We describe a method for successfully using the large scale wind stress and SST data around the site to compute the advection in the Ekman layer and close the heat (to 15%) and TKE (to 30%) budgets. The advection estimates mimic the episodic character of the heat and PE contents and are clearly important on the short, storm time scale. The TKE budget is still complex, we cannot be certain of the relative importance of surface production, shear production and advection but it is suggested that mixed layer deepening is dominated by wind-forcing even during times of significant cooling.

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UPPER OCEAN DYNAMICS

A HYDROGRAPHIC SECTION AT 152W

A hydrographic section was made along 152° between Hawaii and Kodiak, Alaska during May 1984. Approximately 100 stations were occupied with CTD lowerings and bottle samples for salinity , oxygen, nutrients, and tritium to 1500 m or to the bottom on alternate stations.

Dynamic calculations of geostrophic current with respect to 1500 dbar reveal bands, order 100 km wide, of alternating currents up to 25 cm/sec near the surface and up to 3 cm/sec near the bottom from the Hawaii Ridge north to 28N; bands of currents of order 5 cm/sec near the surface, small at depth, from 30°N to 47°N. Geostrophic currents are low between 47°N and 55°N. The westward Alaska Current appears between 54°N and the Aleutian Island Chain.

A section of potential vorticity shows strong northward gradients above the main pycnocline and homogenization on density levels below the pycnocline. Many properties, both passive and active, show strong doming of isopleths in the Subarctic Gyre. The crossing of isopycnals by other property isopleths is consistent with the idea of upward motion under regions of positive wind stress curl.

Silicate is the property that has the strongest signature in the deep and abyssal layers with an abyssal maximum under the Subarctic Gyre. There is a transition region around 41-42°N where the abyssal maximum disappears. Other properties exhibit hints of similar structure.

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Thomas Dillon & Douglas Caldwell

MILDEX MICROSTRUCTURE

Earlier work in the sea and in lakes has suggested that simple models originally developed to explain turbulent transport in the atmospheric boundary layer may be applicable to mixing near the surface in the sea. The MILDEX data set will be useful in determining the generality of the boundary layer models.

Over 200 WAZP II (Wave Zone Profiler) casts were made in MILDEX, under a variety of surface conditions. The MILDEX data consists of microscale observations of shear, temperature, and conductivity in the depth range 0-100 M. Preliminary analysis of the MILDEX data was done in FY84, and a data report has been produced. Analysis will continue through FY86.

We can estimate energy dissipation rates and eddy mixing coefficients from the WAZP II profilers. We expect that the larger-scale shear measurements made by Richman and deSzoeke and Reiger's Doppler Log Measurements from WECOMA, as well as FLIP measurements by Weller, Price and Pinkel, will help us understand the larger-scale context of the turbulence observations.

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OCEANIC CURRENT RESPONSE TO ATMOSPHERIC FORCING

The two and three-dimensional response of strong ocean currents to atmospheric forcing is studied using numerical simulations. In particular, surface cooling is explored as a possible mechanism for explaining. an observed 100 km southward shift in the mean position of the Gulf Stream during winter. The cooling increases in the downstream direction and in the direction of highest sea-surface temperatures. In the immediate vicinity of the concentrated horizontal temperature gradient associated with the strong current system, most of the the flow changes are induced by the cross-stream cooling gradient. The magnitude and direction of the cross-stream circulation is highly dependent on whether or not a vertical mixing of momentum occurs when the water column convectively adjusts in response to the surface cooling (Adamec and Elsberry, JPO, 1985). A weak cross-stream flow toward the higher sea-surface temperatures occurs in the surface layer if momentum mixing does not occur, whereas a stronger flow toward lower sea-surface temperatures results if momentum mixing does take place. In the regions where the vertical shear is not large, the responses in the flow fields are due solely to the along-stream pressure gradient induced by the prescribed along-stream cooling gradient. The response of the three-dimensional simulations is very similar to the two-dimensional simulations in the immediate vicinity of the front. The cross-stream response due to horizontal cooling gradients is not large enough to displace the Gulf Stream appreciably southward in any of the numerical simulations. By contrast, a moderate increase in the zonal wind stress is more effective in displacing the core of a strong current system than are very strong gradients in the surface cooling.

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RUSSELL L. ELSBERRY

OCEANIC RESPONSE TO ATMOSPHERIC FORCING

The basic objective of this research is to understand and predict those changes in the upper-ocean variables that are related to atmospheric forcing. In a numerical study of the short-term ocean response to atmospheric forcing (Elsberry, Sandgathe and Winninghoff, JPO, 1984), very realistic responses to extratropical cyclones are simulated. Surprisingly large amplitudes and small horizontal scales are found in the tropical and subtropical sea-surface temperature predictions. Elsberry and Adamec (Predictability of Fluid Motions, 1983) and Adamec and Elsberry (JPO, 1984a) describe the sensitivity of these ocean mixed-layer model simulations to variations in the magnitude of the surface forcing. The sensitivity is strongly a function of season. These tests demonstrate the importance of accurate wind speed specifications for ocean modelling. The effect of using averaged atmospheric forcing for driving ocean prediction models has been studied (Adamec and Elsberry, JPO, 1984b). Mixed-layer model simulations over 30 days at Ocean Station Papa were compared for various time averages of the atmospheric forcing. Both the details and the trends in the mixed-layer depth and temperature deviate significantly from the control run when the length of the averaging period is increased. Forcing calculated from the bulk aerodynamic formulae using averages of the atmospheric variables produces better simulations of the mixed-layer depth than does the case in which the averaging is done after the 3-hourly fluxes are calculated. By contrast, the better sea-surface temperature predictions are produced when the averages of the 3-hourly fluxes are used as forcing.

The primary thrust in the research has been in ocean response to hurricane forcing. An analysis of NAVOCEANO current measurements in Hurricane Frederic indicates an immediate response in the inertial currents at all depths to the hurricane passage. The horizontal and vertical scales and propagation rates that are calculated for the near inertial waves appear to be consistent with analytical and numerical studies. This observational study is being expanded with additional current meter arrays to obtain a more three-dimensional view of the response. Numerical studies with a sophisticated embedded mixed-layer ocean circulation model are continuing for comparison with the observational studies. Project personnel also participated in a successful experiment in Hurricane Josephine during October 1984. Three of the four drifting buoys with attached 200 m thermistor chains were deployed at precisely the planned locations and they transmitted unique oceanographic and atmospheric observations throughout the hurricane passage.

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PROF. CHARLES C. ERIKSEN

UPPER OCEAN DYNAMICS

This project is concerned with measurements and theories of upper ocean phenomena. Our approach is process-oriented; we focus on the problems of seasonal thermocline formation and decay, particularly the near-inertial internal wave and mixing components.

At present we are analyzing two four-month time series of current and density profiles taken in opposite seasons at a site in the northwestern Sargasso Sea (34° N, 70° W). These data were taken using a moored upper ocean current and density profiler (the PCM) which collected profiles from 30 - 200 m. depth at 4 hour intervals from April - August 1983 and November - February 1983-84. Preliminary analysis indicates rather strong differences in near-inertial internal wave energy in the two different seasons. Density data indicate the evolution of temperature-salinity characteristics during warming and cooling seasons. In particular, seasonal thermocline density ratios seem to remain fixed during seasonal thermocline deepening and erosion.

We are now preparing to use 4 PCMs as part of a moored array in FASINEX, a frontal air-sea interaction experiment to take place in a region of fronts within the subtropical convergence south west of Bermuda. The plan is to observe changes in near-inertial internal waves in the vicinity of a front. The observations will be made from January to June, 1986.

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DAVID L. EVANS

FASINEX SHIP OF OPPORTUNITY PROGRAM

The ship of opportunity XBT program is collecting XBT section data twice monthly between 30°N and 25°N near 70°W in support of the remote sensing studies of the subtropical convergence front as a part of FASINEX.

As part of the investigation of the subtropical convergence front, we have begun an XBT survey between 30°N and 25°N along a line between New York and San Juan. Thirty XBT's are dropped on each leg in such a way as to densely sample the frontal area identified by satellite IR imagery and less densely sample the whole 5° line. The data are collected from a Sea-Land container ship which makes a round trip every two weeks. Our observer makes every other ship, so that in a typical month, the line is sampled in the first week southbound and the second week northbound.

Data collected between June 1984 and January 1985 have been analyzed and compared with satellite derived sea-surface temperature fronts. Although the comparisons have not been completed, it appears that the positions of the front determined by satellite and XBT sections agree to within 10 km, which is excellent considering the coarse resolution (4 km) of the satellite data used, as well as the XBT station spacing ($\geq$ 10 km). Additionally, the position of the front in the seasonal thermocline correlates very well with the SST front, although multiple SST fronts are often found. These results will be presented at the FASINEX planning meeting.

A sea-surface temperature measuring system has been built and integrated with the ship's satellite navigator. Engine intake temperatures are recorded every five minutes and stored with position on a microcomputer floppy disk. The technician will change disks every two weeks, permitting the system to run continuously. In addition to providing more detailed frontal location information, we will also develop a large calibration data set for improving the satellite/SST algorithm in tropical areas. The system will become operational the week of February 22.

Beyond its support function, this program is providing a unique time series of the frontal system over a period of two years. The strength, location, multiplicity and seasonal variation of the fronts will be analyzed.

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DAVID L. EVANS

TRANSPORT MEASUREMENTS OF THE BRAZIL CURRENT

Program Objectives

To address the following questions:

1. What is the southward transport of the South Atlantic Western Boundary Current past the seamounts at 20°S?
2. Is there a barotropic Brazil Current?
3. Does Antarctic Intermediate Water flow northward or southward along the coast of Brazil between 32°S and 20°S?
4. Does the transport increase downstream?
5. How strong is the transport in the recirculation region near 30°S?
6. Is there a seasonal signal in the transport?
7. What is the horizontal character of the Brazil Current between 20°S and 32°S? Is it characterized by meanders and eddies or does it flow smoothly along the 200 m isobath?

Present Status and Progress Over the Past Year

Joint funding with NSF has lead to the installation of seven Pegasus transponder sites between 20°S and 24°S. The transponders were deployed in April 1983 and revisited in October 1983 and October 1984. Work to date has addressed all of the above questions at 20-24°S. Remote sensing work (analysis of LAC and GAC AVHRR data) has begun to address these questions with wider geographic scale.

We have made arrangements with the Brazilian Navy Hydrographic Office (DHN) to use their ships. The first such cruise was in October 1984, the next is scheduled for April. The Brazilian space agency, INPE, is collecting two passes per day of AVHRR data and sending them to URI. We have provided large capacity disk storage capability to their data acquisition computer in order to accomplish this.

The plan of the original proposal is delayed by about 3 months due to ship scheduling problems. Pegasus transponders will be deployed between 30-32°S next month. Preliminary hydrographic survey data has been obtained from DHN to aid in locating the transponder line.

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D. FARMER

ACOUSTIC OBSERVATIONS FROM USS DOLPHIN

Observations of acoustic backscatter were made from the submarine DOLPHIN, in conjunction with shear and temperature microstructure measurements made by T. Osborn. Data collected during a cruise in October 1984 have revealed backscatter features within the upper 50m of the water column. Bubble clouds are a prominent feature of the near surface zone and have a profound influence on ambient noise generated by the air-sea interaction process (D. Farmer & D. Lemon, J.P.O., 1984). Most prominent were the clouds of bubbles formed by breaking waves. The data are being analyzed to estimate bubble population densities and, especially, the spatial distribution of the clouds under different meteorological conditions. We plan to use simultaneous Doppler data to estimate their vertical velocity and to relate the results to wind speed, air-sea temperature differences and the surface wave field (which was acoustically observed also). In addition to the analysis of sound scattered by bubbles, we also observed various biological phenomena, including, in one case, a dense school of fish lying ahead of the submarine. The microstructure data will be examined for signatures of biological activity (fish wakes).

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RANA A. FINE

STUDY OF THE AGULHAS RETROFLECTION USING FREONS

Research in the past year has focused on analysis of freon and hydrographic data (A.Gordon) collected as part of the Fall 1983 Agulhas Retroflection Cruise (ARC). The conservative tracer freon has been used to show the importance of Mode Waters formed north of the Subtropical Convergence (McCartney, JMR, 1982) in ventilating the subtropical gyres of the South Atlantic and Indian oceans. The outflow waters from ARC, as compared to the inflow, show thick ventilated layers of high freon. In the temperature range 14 to 8°C, three distinct modes were observed as freon maxima. Significant increases in density (0.2 sigma-theta) were found to occur along the path from the Mode Water source region, showing the non-isopycnal character of mixing with older water. Mode Waters near the source are characterized by large negative salinity anomalies and high freon saturations. This correlation has been used to determine a background age of the Agulhas Region thermocline on the order of ten years. The shipboard measurement of freons, which were made using the gas chromatograph system of Weiss and coworkers at Scripps, enabled us to achieve mesoscale sampling resolution. This resolution meant that the data could be used to determine the origin of a large anticyclonic eddy situated off the west coast of Capetown, South Africa. The temperature-salinity characteristics of the eddy were very much like the South Atlantic thermocline (Gordon, SCIENCE, 1985). However, a convection model calculation done with D. Olson (Schmitt and Olson, submitted to JGR), run with the additional constraint of freon age, suggests that the eddy was only a few months past convection at the time of sampling. In addition, the calculation showed that the eddy had acquired its characteristics through cooling of South Indian thermocline water.

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Frank S. Henyey

INTERNAL-WAVE NONLINEAR INTERACTIONS BY THE EIKONAL METHOD

We have been involved in the study of transport of small-scale internal waves through interactions with the oceanic internal wave field. Our technique is to do Monte Carlo calculations, using the eikonal approximation. Our results are at variance with weak-interaction calculations, and we are obtaining new information on microstructure statistics.

We showed that weak-interaction theories are inadequate to treat many aspects of the nonlinear interactions in the internal-wave field, and established that the eikonal technique is appropriate.

We created a large data base of Monte-Carlo test-wave trajectories through various simulated internal-wave fields.

A paper describes the results we obtained for the spectra of various quantities for horizontal wave lengths shorter than one kilometer (Flatté, Henyey, and Wright, 1984). We find that the spectra for horizontal wave number, vertical wave number and frequency evolve toward Garrett-Munk spectra. This result is independent of initial conditions of the background internal-wave spectrum, and of the overall strength of the background. These results lead to the conclusion that the Garrett-Munk spectrum is universal in the sense that nonlinear interactions force the spectrum to evolve toward GM.

We also find that there is a flow towards higher frequencies consistent with a picture of low-frequency internal-wave sources and have investigated the flow through wavenumber-frequency space.

Our numerical data will be used for studying correlations between small-scale and large-scale waves, and in particular for investigating the statistics of breaking waves which we believe are related to microstructure patches.

We are beginning to apply the same technique to the problem of the interaction of surface waves with internal waves. Previous calculations [Watson, West and Cohen (1976), Olbers and Herterich (1979)] have disagreed in the energy transfer rate by two orders of magnitude, from insignificant on the scale of internal-wave energetics to very significant.

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N. P. FOFONOFF

MESOSCALE EDDIES IN THE WESTERN NORTH ATLANTIC

The objective of the study is to describe the mesoscale eddy field of the western North Atlantic by its eddy intensity and a representative time scale based on moored current meter records. The time scale is estimated by computing the midpoint of the low frequency spectral kinetic energy distribution. The time scale varied from 40 to 60 days in the Gulf Stream and exceeded 150 days in the ocean interior to the south and east of the active Gulf Stream region. Time scales as short as 10 days are found near the ocean bottom where topographic effects predominate. The study includes current meter data from recent (1984) moored arrays in the region.

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CARL A. FRIEHE

AIRCRAFT RESEARCH AND COORDINATION FOR FASINEX

The Frontal Air-Sea Interaction Experiment (FASINEX) is scheduled for January-March, 1986, in the Atlantic Ocean Southwest of Bermuda. The objective is to study the physics of the interactions of the atmosphere and ocean in the vicinity of an oceanographic temperature front.

For the measurements in the atmospheric boundary layer, research aircraft will be heavily utilized. Current plans call for the participation of the NCAR Electra, NASA P3 and C130, and the NRL P3A. Other aircraft may also participate. My proposed research centers about two aspects of the FASINEX aircraft program as follows.

In the FASINEX project, I have the role of aircraft coordinator to arrange for the participation of the aircraft and coordinate the measurements to meet the research objectives. This will be an ongoing task in the period January 1, 1985 to December 31, 1985.

Also, I plan to work cooperatively with the Naval Research Laboratory to instrument one of the NRL P3A's with the "radome gust probe" technique for the measurement of boundary layer winds and turbulence in FASINEX. This will require the purchase of equipment (some is being purchased by NRL in this cooperative program) and an extended visit at NRL and PAX River Naval Air Test Station to instrument and test fly the P3.

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TERRENCE M. JOYCE

KUROSHIO EXTENSION CTD SECTIONS

Two meridional XBT and CTD/O_2 sections have occupied the Kuroshio Extension in the autumn of 1983 along the longitudes of 165°E and 175°W. Both sections were repeated the following year (1984). The sections spanned the Kuroshio Extension from the subtropical gyre to the subpolar gyre between nominal latitudes of 28°N and 43°N. All stations were deep (bottom) casts. The western pair of sections was east of the Shatsky Rise and west of the Emperor Seamounts while the eastern sections were to the east of the Hess Rise. The project is being undertaken cooperatively with William Schmitz who has deployed long term current meter moorings in the region. The repeated CTD/O_2 sections are being analyzed to reveal water masses and zonal baroclinic transport in Kuroshio Extension. A manuscript (Joyce, T., Deep-Sea Research, submitted) has been written describing the hydrography from the 1983 cruise. Work is now underway to complete the analysis of the 1984 sections and to combine the hydrographic and current meter results.

From the 1983 sections, we see that the baroclinic flow across 165°E is concentrated into two eastward jets 100 km wide which can be identified with the eastward extension of the Kuroshio and Oyashio (subarctic) fronts. These two narrow zones of eastward flow are embedded in a broader zone of weak, baroclinic transport to the west. While the signatures of the Kuroshio and subarctic fronts are still evident at 175°W, this section is dominated by eddies having meridional scales of 100-200 km. One of these eddies appears to be a detached warm-core ring of Kuroshio water.

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GREG HOLLOWAY

DYNAMICS OF SMALL SCALE VARIABILITY

The dynamics of small scale variability of the open ocean is to be investigated by two approaches: (a) direct numerical simulation and (b) statistical dynamical closure theory. Research will commence in January 1985 and be concluded over a three year period.

A comprehensive program will include investigation both in 2 dimensions (vertical plane) and in 3 dimensions. Research in 2D will be concerned primarily with the detailed testing of theoretical hypotheses by means of numerical simulation. Specific testing will address (a) distribution of energy in full frequency-wave vector space, (b) origin of vertical buoyancy flux, (c) adequacy of theories of strong wave-wave interaction and (d) adequacy of theories of scale-separated interactions. A particular study will address the role of earth's rotation modifying energy transfer to dissipation scales leading possibly to unexpected, significant influence upon vertical buoyancy flux.

Numerical investigations in 3D are more severely constrained by computational resolution. 3D experiments will aim at the interactions of internal waves with non-propagating vortices as well as examining the principle differences between 2D and 3D internal wave dynamics.

Association with field programs will be maintained with special emphasis on three questions: (a) the relationship of occurrences of regions of strong dissipation relative to large scale features, (b) scaling of overturning lengths and energy decay times, and (c) instrument deployment strategies with regard to discriminating waves from vortices.

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NUMERICAL STUDIES OF THE SOUTH ATLANTIC AND SOUTH INDIAN OCEANS: BOUNDARY CURRENTS AND WATER MASS PROPERTIES

As the initial phase of several years' effort, we have begun the design, development, and testing of several kinds of numerical models of the region of the Southern Ocean centered upon the South Atlantic and South Indian Oceans. These models include quasigeostrophic and primitive equation physics for limited area and global domains, including boundary conditions that allow a 'parameterization' of the interactions with other ocean basins.

Initial studies with a limited area model of the Agulhas Current have shown great promise in understanding the development and maturation of Agulhas eddies, their role in the retroflection process, and their influence upon the properties of the South Atlantic. Two papers are in preparation related to this component of our work.

A large-scale model of the entire South Atlantic and South Indian Oceans is under development, including realistic geometry and bottom topography in a primitive equation model with relatively high vertical resolution (15 levels). First the influence of open boundary conditions at the northern boundary, the Drake Passage, and the Circumpolar Current south of Australia will be studied; then the model will be used to understand the nature of water mass formation in this multi-ocean domain. In particular the influence of other ocean basins (not included explicitly) on water mass formation processes in the South Atlantic-South Indian-Circumpolar Ocean will be determined through a sequence of model calculations. We intend, when computing resources are available in future years, to extend this work to eddy-resolving calculations in which all these important processes occurring in this domain of the World Ocean are explicitly taken into account.

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Nelson G. Hogg

ABYSSAL CIRCULATION OF THE WESTERN NORTH ATLANTIC
A COHERENT ARRAY FOR HEBBLE

In classical dynamical oceanography there are two kinds of circulation; that driven by the wind at the ocean surface and that forced by thermohaline convection in isolated water formation regions. This project is aimed at understanding a third type of circulation -- eddy driven -- that is forced through the time averaged stresses exerted by the intense eddy field near the Gulf Stream. Until now work has been mainly descriptive in nature. Through the combined measurement of water properties and in situ currents we have attempted to describe the nature of the general circulation near the Gulf Stream with a special emphasis on the deep water.

It appears the whole water column north of the Stream moves westward practically barotropically between the Grand Banks and the New England Seamounts and transports as much as 40 Sv, nearly half of the Gulf Stream transport and maybe four times what is carried in the Deep Western Boundary Current. In the vicinity of the Seamount Chain this flow intersects the Gulf Stream and returns to the east by sliding down along density surfaces and turning east under the Stream so as to conserve its potential vorticity. In the process it has been in close contact with the thermohaline DWBC and obtained some of its tracer properties (e.g. higher oxygen, freon, etc.) which then are advected eastward under the Stream and so distributed into the ocean interior.

We are presently fleshing out the above description by mapping various tracers on density surfaces, compiling long term current measurements in the region and developing simple advective-diffusive models. Our ultimate goal is to be able to quantify the eddy-mean flow interaction terms to discover exactly how this powerful deep recirculating flow is driven. With this goal in mind a small array was set to the north of the Stream in the HEBBLE area. Instrumentation is primarily deep but the array was designed to be coherent on the eddy length scale. With this information we hope to gain a better understanding of the eddy field, how they are forced and what their averaged Reynolds stresses are.

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ROBERT L. HANEY

EDDY GENERATION MECHANISMS IN THE CALIFORNIA CURRENT SYSTEM

A numerical modeling effort is underway to investigate processes responsible for the generation of observed synoptic scale variability in the California Current region. A 15-level primitive equation model with surface layer physics has been adapted to include an idealized Mendocino escarpment and continental slope along a straight meridional coastline. The model is in sigma coordinates (non-dimensional depth) and has open boundaries (radiation condition) on all but the eastern coastal boundary. We are presently studying the response of idealized flows over the escarpment for which there are analytic solutions. Model sensitivity studies will be made to determine the dependence of the solutions on the parameterization of sub-grid scale processes and on the choice of boundary conditions on the flow at the bottom, on the slope and at the eastern boundary. We expect to study the eddy generation process in the presence of a number of different flow regimes which have been observed upstream of the Mendocino escarpment. The ultimate goal is to understand and predict the generation of synoptic-scale eddies which are being observed south of Cape Mendocino in the OPTOMA program.

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Michael Gregg and Wayne Nodland

UPPER OCEAN MIXING PROCESSES

Our long-range goal is to develop a quantitative understanding of mixing processes in the upper ocean. This is done by making microstructure observations with the Advanced Microstructure Profiler (AMP) in conjunction with other measurements that can define the larger-scale processes driving the mixing. For example, the Drifter cruise was run off San Diego in October 1982 to study mixing produced by internal wave breakdown. A time series was maintained with AMP alongside a drifting drogued buoy and auxiliary data were collected with CTD mapping around the buoy and with a time series of Expendable Current Profilers (XCPs). Persistent mixing patches, lasting for several days, were found associated with a near-inertial feature. Statistics of the patches were obtained and compared with predictions from kinematical internal wave models. Preliminary results appeared in the Proceedings of the 1984 Hawaiian Winter Workshop and a full paper will be submitted to JPO in early 1985.

Other studies have been done of winter-time convection during a cold air outbreak off the east coast of the U.S., and mixing in thermohaline intrusions. During the cold-air outbreak the oceanic boundary layer was found to follow similarity scaling similar to convecting atmospheric boundary layers; intense turbulence filled mixed layers that deepened to 180 m in 36 hours (Shay and Gregg, NATURE, 1984). Intense turbulence was also found in thermohaline intrusions that appeared to be caused by a combination of double diffusion and shear instability (Larson and Gregg, NATURE, 1983). The shear in the intrusions was due to a near-inertial feature.

Future work is planned in Sept/Oct 1986 in the main thermocline as part of the multi-investigator experiment PATCHEX. The goal of PATCHEX is to obtain a 3-dimensional time histories of mixing events produced by internal waves using AMP, the NRL chain, a Richardson number float, and FLIP. One of the objectives is to test the hypothesis that near-inertial features are major factors in producing internal wave breakdown. If correct, this will change the prevailing approach to estimating bulk mixing rates.

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ARNOLD L. GORDON

STRATIFICATION AND CIRCULATION OF THE AGULHAS CURRENT RETROFLECTION

A Hydrographic data set obtained from R/V KNORR within the Agulhas Retroflection reveals an energetic Agulhas current carrying up to 70 SV within a narrow axis. After separation, the Agulhas curves back (retroflection) towards the Indian Ocean, undergoing an equatorial deflection over the Agulhas Plateau. The retroflection pattern entraps a large pool of Indian Ocean thermocline water which is modified by the winter atmosphere, forming subtropical mode water of the South Indian Ocean. The Indian Ocean thermocline at mid depth is influenced by two varieties of subantarctic mode water. This leads to a rather complex water mass stratification, with numerous minimum/maximum layers in salinity, oxygen and nutrients. Deep water stratification is equally complex as the deep waters of the Atlantic and Indian Oceans interact. Division of the Agulhas Return Current from colder Atlantic derived water to its south is marked by a very intense front near 40°S. South of the front are isolated warm core anticyclonic eddies strongly modified by the winter atmosphere. Their origin is not clear. The retroflection apparently spawns large anti-cyclonic rings, two of which were observed in 1983, west of the main retroflection. The ring centers are marked by deep winter mixed layers. Between the African coast and the centers is a flow of Agulhas water into the Atlantic which is not returned on the seaward side of the eddies. This Agulhas branch introduces 14 SV of Indian Ocean water into the South Atlantic (Gordon, 1985). It is probable that Indian to Atlantic transfer of warm water is part of the global scale circulation cell related to production and Atlantic export of North Atlantic Deep Water.

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ARNOLD L. GORDON

BRAZIL-FALKLAND CONFLUENCE: MESOSCALE AND FRONTAL THERMOHALINE STRUCTURE

An October 1984 hydrographic data set obtained from R/V WASHINGTON within the Brazil-Falkland Confluence region reveals a complex distribution of warm and cold meso-scale features. The warm thermocline stratification associated with the Brazil current forms two poleward meanders or branches separated by a cold core cyclonic eddy, composed of slope and subantarctic water, centered near 40°S and 50°W. The western branch separates from the continental slope near 39°-40°S on "collision" with the Falkland (Malvinas) current. The warm water protrudes further south where it spawns small anti-cyclonic warm core eddies near 43°S. These eddies drift to the southeast perhaps at a rate of 6 cm/sec. They are strongly altered by the winter atmosphere, which forces density ratio values as low as 1.4, and hence salt finger enhanced vertical mixing is likely. The energetic rims of the warm eddies display some of the characteristics of the warm core rings associated with the Gulf Stream system, with many filaments of contrasting water types. The layering of Subantarctic Mode Water and Antarctic Intermediate Water within the slope and thermocline regions reveals some differences in salinity and oxygen levels as compared to data obtained in 1979 and 1980.

The October data set combined with the data obtained during the November and December 1984 cruises of WASHINGTON to the east (Roden, chief scientist) and north (M. McCartney, chief scientist) of the Confluence region offer a large scale synoptic view of the Southwest Atlantic.

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Carl H. Gibson

Intermittency of oceanic mixing processes

ABSTRACT

The purpose of the study is to develop statistically reliable methods of sampling oceanic turbulence and mixing processes and interpreting the data. Microstructure measurements reveal the precise physical mechanisms but must be interpreted carefully because of the extreme intermittency of the viscous and thermal dissipation rates ϵ and χ. Available data sets have been examined using Monte Carlo methods to account for the effects of noise, sensor spatial resolution and undersampling, and are found to have nongaussian pdf's which are indistinguishable from the lognormal distribution predicted by the cascade model of Gibson (AIAA J. 1981), with large values of the intermittency factor $\sigma^2_{\ln X}$ in the range 3-8, where X represents either ϵ or χ. Confidence intervals for the maximum likelihood estimator of the mean of a lognormal random variable, previously unavailable, were derived using Monte Carlo and theoretical methods, and will be published in paper by M. Baker and C. Gibson. From the confidence intervals it is shown that the commonly accepted discrepancy between the vertical diffusivities inferred from microstructure measurements in the main thermocline and those inferred from bulk properties is statistically insignificant: $0.02 < K_v < 2.8$ cm^2/s from Gregg (JPO 1977) versus about 1 cm^2 from bulk models such as Munk (DSR 1966). Minima in $\bar{\epsilon}(z)$ and $\bar{\chi}(z)$ at the seasonal thermocline depth and at the high velocity core depth of the equatorial undercurrent, which have been inferred from individual profiles, are shown to artifacts of the extreme intermittency in these strongly stratified layers and have no statistical significance. Microstructure collected by APL/JHU from towed chains will be analyzed to improve the reliability of the inferred pdf's and $\sigma^2_{\ln X}$'s by increasing the sample size and the range of coverage in space and time.

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CATHERINE GAUTIER

SATELLITE-DERIVED NET OCEAN SURFACE RADIATION BUDGET

The surface fluxes influence the ocean surface currents and the mixed-layer heat budget. A specification of the variability of these fluxes is therefore important to better understand the variability of the upper ocean.

The goal of our research effort was to estimate one of the main components of the surface heat flux: the radiation budget from satellite observations, and to quantify its variability in space and time in order to investigate its role in the upper ocean heat budget.

We improved our earlier model (Gautier et al., 1980) to compute the net shortwave radiation flux at the surface from geostationary satellite data by including the effects of aerosols. The improvements, assessed by comparison with the MILDEX surface measurements are of about 2% (Gautier and Frouin, 1985) compared with our previous approach.

Our major effort has been in the development of a method for computing the downwelling longwave irradiance at the ocean surface, in all weather conditions. We have acquired a precise longwave radiation model (Morcrette, 1983), implemented it and ran sensitivity tests on it. The necessary LW model input parameters are computed from geostationary satellite radiances in the visible and the infra-red together with cloud modeling results relating cloud radiative properties to their physical parameters (Stephens, 1978). These physical parameters are, respectively: the cloud coverage, the upwelling and downwelling cloud emissivity, the cloud top temperature and its total liquid water content. The atmospheric temperature and humidity profiles are obtained from NOAA operational soundings. Then, from experimental data, relating atmospheric temperature profiles to cloud liquid water content and from cloud top temperature, we determine cloud base temperature. This procedure has been applied to satellite irradiance data acquired during MILDEX and the computed longwave irradiance at the surface has been compared with surface measurements made on the Acania and on FLIP. The comparison with the Acania measurements provide the best results, with a correlation of .75 and a standard deviation of 18 w/m2 between the two data sets compared (Gautier and Frouin, 1985).

We also compared results obtained from bulk methods (Clark and Bunker) with the surface measurements. This allowed us to compute the biases in the measurement systems and also to estimate the accuracy of the bulk parameterizations. The measurements systems had respective biases of -8 and 22 w/m2 and the bulk parameterizations an accuracy of 18 and -23.5 w/m2, respectively.

We will test the applicability of this method to other data sets (FASINEX) before implementing it to derive surface longwave flux.

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Silvia L. Garzoli

BRAZIL/FALKLAND CONFLUENCE: TIME VARIATIONS OF THE FRONT

An array of three inverted echo sounders have been deployed in the South Atlantic across the Brazil and Malvinas (Falkland) currents. The object of the experiment is to continuously monitor the transport variability of the Brazil current. The instruments were deployed from the R/V PUERTO DESEADO in November of 1984 at 37°58.7'S 51°56.4'W, 37°44.0'S 53°01.6'W and 37°29.3'S 53°49.3'W. Three XBT and CTD sections were also obtained in order to establish the location of the currents and the retroflection at the time of the deployments. The instruments will be recovered in June 1986 and similar XBT and CTD sections will be obtained.

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STUDIES OF THE OCEANIC PLANETARY BOUNDARY LAYER

models are not large for short-term (12-24 hrs) model evolutions. However, when the surface wind speed is relatively low, and the atmospheric lifting condensation level is near the inversion, major differences between the coupled and uncoupled systems are commonly found during the diurnal evolution. Such situations may prevail in the transition from overcast to clear sky regimes. Thus a coupled model system may be most needed to explain the location and time of formation of stratus and fog.

To study the role of interior vertical motion upon the dynamics of the surface mixed layer, an annual period oscillatory motion was prescribed at the base of a seasonally-evolving upper ocean density profile. The results show (Muller, P., R. Garwood, and J. Garner, Ann. Geophys., 1984) that entrainment and vertical mixing may be influenced by this motion, depending upon the phase of the vertical oscillation relative to the seasonal surface heating cycle. Although horizontal advection was not allowed in this first numerical investigation, and there is no atmospheric feedback, this study suggests that seasonal-scale sea surface temperature anomalies of up to 2 C may be created by anomalous vertical mixing due to the passage of long period interior waves.

A usually neglected Coriolis term is found to be significant for the mixing depth of a turbulent boundary layer in equilibrium. The easterly Reynolds stress interacts with the northward component of rotation, causing the exchange of turbulent kinetic energy between vertical and horizontal components. The results show that vertical mixing and mixed layer depth may be enhanced if the surface wind is from the east, and mixing will be reduced if the wind is from the west. This effect may help explain the deep tropical mixed layers in the central Pacific.

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ROLAND W.GARWOOD, JR.

STUDIES OF THE OCEANIC PLANETARY BOUNDARY LAYER

In these studies of the oceanic planetary boundary layer, a variety of problems related to turbulence dynamics, entrainment and air-sea interactions are identified. Mathematical models are proposed and tested for processes including the response of upper ocean density fronts to local atmospheric forcing; interaction between mixed layer entrainment and interior motion; dynamic and thermodynamic interactions between coupled atmospheric and oceanic turbulent boundary layers; and the effect of wind direction upon the vertical penetration of wind generated turbulence into the ocean's interior.

Several numerical experiments with different atmospheric forcing were used to investigate the transient response of upper ocean fronts. The results (Adamec, D. and R. Garwood, J. Geophys. Res., 1984) are consistent with observations of the Maltese front by Ola Johannessen for a case of impulsively increased wind stress parallel to the front, having inertial and Ekman transports across the front. Depending upon wind direction, the frontal structure and near-frontal circulation is affected by mixed layer entrainment. When the wind stress was reduced in the presence of diurnal solar heating, the interior circulation was largely from the shallowed surface mixed layer. However, the surface position of the front can be rapidly displaced from the interior quasi-geostrophic front by the near-surface concentration of wind-driven flow.

A coupled one-dimensional atmospheric-oceanic boundary layer model was evaluated (Davidson, K. and R. Garwood, Dyn. Atmos. Oceans, 1984) in a sensitivity study to determine major differences in the coupled system relative to the behavior of the separate (uncoupled) oceanic and atmospheric models. In general, differences between coupled and uncoupled

BRENT GALLAGHER

CLOSURE FOR SECOND ORDER TURBULENT PRESSURE EFFECTS IN NONUNIFORM, ROTATING FLOWS

We are developing closure expressions to describe the effects that turbulent velocity/pressure-gradient interactions have on the evolution of Reynolds stresses in turbulent flows. These interactions have several, additive components. We have finished deriving and testing successful expressions for the component that arises because of interplay between the turbulence and the strain rate of the mean flow. Currently we are working on the component that comes from turbulent pressures that arise when the turbulence is subjected to rotation, as in geophysical flows. The objective is to permit time and space dependent Reynolds stress components to be predicted in rotating shear flows.

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TIMOTHY W. KAO

OCEANIC FRONT MODELLING

A realistic model of the Gulf Stream (GS) and its frontal structure is of importance not only to the basic understanding of frontal dynamics but also to the applicability of remote sensing techniques, such as satellite altimetry, in monitoring the subsurface Gulf Stream circulation. A model giving a quantitative cross-sectional representation of the Gulf Stream north of Cape Hatteras has been obtained.

The model is based on the full Navier-Stokes and diffusion equations in two dimensions and starts with a stratified ambient fluid. The results show a pycnocline structure in the slope water with a number of isopycnics connected with those of the main ocean pycnocline beneath the Sargasso Sea. The inclined isopycnics form the main density front of the GS. The results also show a well-defined jet with strong cyclonic shear on the slope water side and weaker anticyclonic shear on the Sargasso Sea side. Normalized Gulf Stream transport as a function of the cross-stream distance is also found. The model results are compared with field data. Quantitative agreement is demonstrated. It is also shown that subsurface structural information of the Gulf Stream can be obtained, through the use of the model, from satellite altimetry data and other readily available data.

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KRISTINA B. KATSAROS

RADIATION MEASUREMENTS DURING MILDEX

Our long-term objectives are to understand short- and longwave radiative transfer in all environments and to acquire high quality radiation data for use in developing parameterizations of each component of the radiative heat budget equation for the air-sea interface.

Accomplishments Under Present Grant

Short- and longwave radiative fluxes were measured from R/P FLIP and R/V Acania during the MILDEX (Mixed Layer Dynamics Experiment) in October-November 1983. We calibrated and packaged pyranometers and pyrgeometers as well as surface thermistors for this task, but the data were monitored and recorded by our colleagues, R. Pinkel from Scripps Institution of Oceanography and K. Davidson from the Naval Postgraduate School. A technical report on the time series of the separate terms in the radiative heat budget equation for the sea surface has been produced from the R/P FLIP data and a similar one for the R/V Acania is in progress. Collaboration with colleagues J. Price and C. Gautier in relating these measurements a) to upper ocean modelling and b) to atmospheric radiative transfer calculations are in progress.

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Thomas Keffer

STUDIES ON THE CIRCULATION OF THE NORTH PACIFIC SUBTROPICAL GYRE

This program looks at the mean and time-dependent motions and temperature variability of the eastern subtropical North Pacific, using data from two moorings deployed in July, 1982, along 152°W. This is a two year program, now at the start of its first year. The intention is to gain an understanding of what causes the temperature and velocity variability in this section of the world ocean. This area is particularly interesting because of its remoteness from the eddy generating regions along the western boundaries (in this case, the Kuroshio). In the absence of this eddy "noise", clear signals from wavelike features (barotropic and baroclinic Rossby waves) can be extracted, making the results generalizable to the rest of the world ocean.

Three years of data will be collected. Two are now in hand. We are in the process of assembling the temperature field data base from the XBT ship-of-opportunity program for this area. We are currently working on interpolating the measured velocity field from the first two years of data onto this temperature field. The resulting implied horizontal temperature flux will then be compared to the measured temperatures at the mooring locations. Estimates for the missing vertical temperature flux will then be made.

In this manner, we hope to be able to explain the temperature variability as a function of frequency and wavenumber.

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A. D. Kirwan

Identification of Causes and Effects of Mesoscale Variability in the Eastern North Pacific

The long-term goal of this research is to identify the mechanisms by which mesoscale ocean motions transfer energy between larger and smaller scales. The emphasis in this phase is on deducing mesoscale kinematic characteristics from Lagrangian data obtained in the North Pacific from 1976 through 1978 and appropriate surface wind and hydrographic data. The analysis procedure utilizes a parametric model developed by Kirwan (Tellus, 36A(2), 211-215, 1984) and tested by Kirwan et al., (JGR, 89(C3), 3425-3438, 1984) for quantitatively decomposing the drifter velocities into large scale and mesoscale components. The model also provides information on the spatial structure of the mesoscale flow.

Preliminary results show that the mesoscale in the Eastern North Pacific is dominated by anticyclonic motion with a frequency of the order of about 5 E-6 Hz. Some cyclonic structures are found, however the data suggest that they are neither as intense nor as persistent. The Gulf of Alaska is a region of fairly intense mesoscale activity. The continental shelf region off British Columbia seems to be an area of fairly intense anticyclones. Some, however, are found in the mid-Gulf region. Preliminary results also show that the mesoscale motion are somewhat stronger than suggested by Wyrthi et al., (JGR, 81, 2641-2646, 1976), Kirwan et al., (JPO, 8(6), 1978) and McNally et al., (JGR, 88(C9), 7507-7518, 1983).

As part of the Southern Oceans Studies Special Focus Program, analysis of mesoscale and large scale variability is being conducted in collaboration with the University of Miami group. A detailed comparison has been made between drifter data, satellite imagery and XBT data for several South Atlantic eddies off of Capetown. A consistent picture of the vorticity and horizontal velocity shears within these structures is emerging from these studies.

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Modeling of coastal circulation in a canyon/shelf system

The work for ONR in FY85 focuses on forced flow in narrow, subsurface channels and canyons. If the overlying geostrophic circulation is transverse to the canyon, then there is a resulting pressure gradient near the bottom which will force flow along the channel.

The real question in this analysis involved divergence of the flow in the canyon which forces exchange of fluid and a consequent secondary circulation, analogous to that occurring during coastal upwelling. Flow divergence is caused by variable pressure gradients (horizontal structure of the overlying flow) and by geometry of the canyon (say, by ending at some point).

A second consideration of the analysis is bottom slope and the energetics of pumping deep, denser water up along a sloping canyon. Such a localized upwelling appears to be the source of the Juan de Fuca eddy located south of Vancouver Island during the summer.

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"Coastal Circulation near a western ocean boundary"

Abstract: The linear, continuously stratified, eastern-boundary model of McCreary (1981) is extended to apply to a western ocean boundary and to alongshore wind fields with curl. The model has vertical and horizontal mixing, and both types of mixing are important in the dynamics.

Solutions at the western boundary differ fundamentally from those at the eastern boundary. For winds without curl, the surface jet is stronger and there is essentially no coastal undercurrent. This difference is due to the fact that at an eastern boundary the currents associated with low-order modes leak offshore. For winds with curl, a sizeable undercurrent develops, but only south of the region of the wind.

The existence of this undercurrent is in accord with observations off Somalia, where a southward undercurrent has been observed at 5°N during the Southwest Monsoon. The wind at this time is oriented alongshore, reaching a maximum strength well to the north of 5°N, and is associated with a region of large negative offshore wind curl.

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W.G. LARGE

SARGASSO SEA SEASONAL THERMOCLINE

The scientific objective is to learn how the seasonal thermocline of the Sargasso Sea is established throughout the Spring and Summer. For this purpose we use data from Climate Air-Sea Interaction Drifting (CASID) buoys, which have 125 meter thermistor chains and various meteorological sensors. In April 1983, three buoys were deployed in the vicinity of the Long Term Upper Ocean Study (LOTUS at 34°N, 70°W). During the next four months they drifted throughout the area 32 to 39°N and 59 to 71°W. Collaborative data may be available from the LOTUS moorings (M.G. Briscoe and R.A. Weller) and from AVHRR images processed into SST maps (P. Cornellion and D. Evans).

Of particular interest is the role of the daily thermocline cycle in the evolution of the seasonal thermocline. The daily cycle is evident in the shallow thermistor records (1,4,6,9, and 12 meters depth) and it will be isolated and related to thermocline formation seen in the deepest thermistor records (18,16,34,44, and 54 meters depth). The buoys were often in mesoscale eddies and the question of how their effects need to be treated will be addressed.

An interesting question is: What is the relation between the satellite sensed surface temperature features and subsurface CASID measurements. A recent result shows that an outbreak from the Gulf Stream had warm, fast moving water constrained to within 20 meters of the surface. It is presented in a manuscript being submitted with P. Cornellion and D.E. Evans.

This work includes the technological development of a vector wind stress measurement for use on drifting buoys. Plans for adapting an ambient acoustic noise device (Evans, et al., JGR, 1984) are to be finalized at a workshop to be held at NCAR, March 13-15, 1985.

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DR. KEVIN D. LEAMAN

GULF STREAM RECIRCULATION AND DEVELOPMENT NORTH OF THE BAHAMAS

In cooperation with Dr. T. Rossby of the University of Rhode Island, we are studying the evolution and development of the Gulf Stream as it proceeds northward from the Straits of Florida to the region off Cape Hatteras.

For a period of several years, T. Rossby has obtained bi-monthly velocity and temperature cross-sections of the Gulf Stream off Cape Hatteras using a free-falling acoustically operated current probe called PEGASUS. During the same period and using the same instrumentation and methods, we have obtained repeated cross-sections of the Florida Current in the Straits of Florida at latitude 27°N as part of the ONR- and NOAA-funded sub-tropical Atlantic Climate Study (Science, 1985).

Comparison of data from these two research efforts has revealed some striking similarities in the mean structure of the velocity field of the Gulf Stream. For example, the cross-stream velocities at both locations show a net inflow into the Gulf Stream which appears to be linked to the position of the core (point of maximum horizontal velocity) at any depth. Efforts are now being directed at developing a better theoretical understanding of this phenomenon.

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MURRAY LEVINE

UPPER OCEAN INTERNAL WAVES

Five Aanderaa thermistor chains were deployed aboard the Current Meter Drifter (Richman/de Szoeke) for 19 days in fall 1983 as part of the Mixed Layer Dynamics Experiment (MILDEX). The chains were located below the mixed layer between 70 and 800 m. The buoy was deployed off California at 33°51'N, 126°42'W and drifted northeast at an average speed of 5 cm/s. Preliminary results are outlined below.

INTERNAL TIDE

An analysis of the semidiurnal tide combining the data from the thermistor chains and several VMCM current meters reveals:

- The amplitude and phase of the tide are highly variable in time/space, changing significantly over a time-scale of a few days.
- For a short period (27 to 28 Oct) the signature was consistent with a wave traveling on the interface between the mixed layer and thermocline at about 50 m. The wave was propagating to the north with an amplitude of 7 m in vertical displacement.
- From 29 to 31 Oct the phase of the tidal signal is especially erratic. This period corresponds to the time of significant changes in the low frequency temperature and velocity field.
- During 4 to 7 Nov the vertical displacement is in-phase from 70 to 800 m, indicative of a low mode wave. The direction of propagation is from the southeast with maximum amplitude of 18 m between 500-800 m.

INTERNAL WAVES

Spectral analysis of the vertical displacement field was performed and compared with the Garrett-Munk model (GM). Some interesting results of the analysis include:

- Not surprisingly, the spectra generally follow the GM spectrum; the data scale with N over the range of 8 cph at 85 m to 2 cph at 450 m.
- Vertical coherence between 85 and 450 m is significant in two bands around 1 and 3 cph indicating a low number of modes at high frequency.

FINESTRUCTURE

Many features in the data recorded by the thermistor chains were not due to internal waves. Layers of low temperature gradient or inversions are present occasionally in the data. These layers range from 3 m thick at 85 m to a maximum of nearly 30 m at 800 m depth; the horizontal extent of these features is of order 1 to 2 km.

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Edward R. Levine

FRONTAL MIXING IN THE GULF STREAM

In FY 86, the project "Frontal Mixing in the Gulf Stream " focuses on data reduction, analysis and interpretation of results from a major field experiment conducted during FY 85. The objectives of this program are to examine local transport, stirring, and mixing processes along the dynamically active region of the Gulf Stream Front in the region between the Blake Plateau and the area downstream of the New England Seamounts near 60°W. This effort is a joint Norwegian-U.S. effort combining the water parcel tracking capabilities of our recently developed isopycnal (density following) Swallow floats with the toyoing survey capabilities of the instrumented Batfish.

These studies will be conducted at site specific regions along the northern boundary region of the Gulf Stream where entrainment, upwelling, stirring, or cross frontal mixing are important physical processes. In particular, phenomena under study will include upwelling/mixing in the region near the Charleston Bump (a bathymetric feature near 32°N), entrainment /interleaving in the region east of Cape Hatteras, shingle mixing and dynamics east of Hatteras, and interleaving and mixing in the New England Seamounts region.

Our approach to data analysis will will be oriented towards determining the dominent scales of water mass exchange and mixing at the various sites - estimating distributions of layer thicknesses, scales of cross-stream penetration, and downstream coherence. We will estimate fluxes of oxygen, salt, heat and density across the dynamical front. Eddy fluxes of oxygen and salt can be determined from vertical averages of the quantities $u'O_2$ and $u'S'$. We will also consider the role of double diffusion and other mixing mechanisms by estimating their activity levels and examining T/S structure along density surfaces. The role of mesoscale motions such as meanders in stirring, vertically advecting , and shearing water parcels will be evaluated from a comparison of shipboard data with satellite imagery. Circulation patterns in features such as shingles and intrusions will be compared with existing models. Also a comparison of physical parameters with synoptic biological/chemical tracers will be made.

This project has been jointly funded by ONR and the NUSC IR-IED Program in the past. We will once again pursue internal funding under this program. The NUSC role in the analysis phase of this project will include all Swallow float, hydrographic, XBT and XCP data analysis as well as collaboration with other investigators on other data sets.

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ARCTIC INTERNAL WAVES

A group of investigators have proposed a coordinated effort known as AIWEX (Arctic Internal Wave Experiment) to measure the internal wave field in the Arctic Ocean. One motivation of this research is that the Arctic is a place where some aspects of the internal waves may be different from those measured in other upper-ocean experiments. Preliminary evidence suggests that spectral levels are significantly lower than those of mid-latitude (Levine, Paulson and Morison, JPO, in press). Perhaps the lower energy level can be related to the unique forcing and dissipation processes present in the Arctic.

This project is focused around the deployment of temperature and conductivity sensors to be moored from the ice during AIWEX. Planning and instrument development is nearing completion in preparation for the field program to occur in March-April 1985 about 200 nautical miles north of Prudhoe Bay, Alaska. The major scientific goals of this project are:

- to verify the apparent low spectral levels,
- to estimate in detail the spectral and coherence structure of the high-frequency internal wave field,
- to compare variations in the internal wave field with variations in the surface stress, eddy field, and boundary layer dissipation,
- to aid in the detection and description of the eddy field,
- to investigate the importance of non-internal wave finestructure in the measured statistical quantities.

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R. G. Lueck

Ocean Turbulence

The long range goal of ocean turbulence research is to determine the role of turbulence and other microstructure in the circulation of the ocean and in the vertical flux of momentum, heat and salt. The rate of dissipation of turbulent kinetic energy will be estimated from vertical profiles made in the California current system during the 1982 DOLPHIN cruise and profiles collected during the MILDEX (Mixed Layer Dynamics) Experiment. Data from the DOLPHIN trip will be used to compare the horizontal and vertical signatures of microstructure and to examine mixing at the boundaries of intrusions. Time series at fixed locations always show one or more layers that remain turbulent for up to 24 hours. The data will be used to examine the temporal variability of turbulent layers. The DOLPHIN data is being analyzed with Dr. Yamazaki. The MILDEX data spans the rising edge of a storm and will be used to study the response of the mixing layer, to make a mixing layer budget, and to examine the delayed growth of turbulence in the thermocline. We will also participate in the analysis of some of the data taken with the USS DOLPHIN during the cruises in April and Fall of 1984. Our effort will concentrate on the mixing layer-thermocline interface measurements. We will also continue development work on the air-foil probe including an examination of the usefulness of the newly developed piezo-electric films.

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JOHN L. LUMLEY

MODELING OCEAN TURBULENCE

Use of computational modeling, experimental data, and theoretical analysis to characterize, parameterize and model near-surface fluxes (in water and air) of latent and sensible heat, salt, gases, droplets and momentum and the interdependence of these fluxes, as well as wind-wave interaction, wave-turbulence interaction, and the dynamical effect of all these on the turbulent transport. A number of recent papers have appeared, e.g.: Kitaigorodskii, JPO 1983, 1984a, b; Kitaigorodskii & Lumley, JPO 1983; Kitaigorodskii, Donelan, Lumley & Terray, JPO 1983; Lumley & Terray, JPO 1983.

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James R. Luyten

EXPLORATION OF THE AGULHAS CURRENT

The Agulhas Current system is the western boundary current for the gyre in the southern Indian Ocean, flowing poleward along the coast of southern Africa. This current, together with its associated recirculation and eddy field, is the most energetic oceanic feature in the southern hemisphere, both in terms of air-sea interaction and mesoscale variability. Nearly all that is known about the Agulhas comes from analyses of hydrographic data and satellite imagery. While this is a rich and varied data set for interpretation, there are few direct observations of the current field per se.

To explore this current system, particularly the retroflexion of the Agulhas, we will deploy a long-term, large-scale mooring array. The moored array consists of ten moorings, deployed for a period of two years, with current meters at 200, 700, 1500 and 4000 meters depth. The moorings will be deployed from the southwestern end of the retroflexion region, near 15°E to the region where the current separates from the continental margin.

We will conduct an extensive XBT survey of the edge of the current (15°C at 200 meters depth) and deploy several satellite tracked drifters to determine the synoptic path of the current.

The satellite imagery (NOAA/TIROS AVHRR) data is being collected and will be analyzed to make contact with this historical data and provide data on the evolution of the Agulhas Current system.

Simple analytical models with active buoyancy forcing are being examined to explore the dynamics of the retroflexion process.

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James J. O'Brien, Principal Investigator

STUDY OF GEOSTROPHIC FRONTS
by Benoit Cushman-Roisin

Understanding of the time dependence of upper ocean fronts is motivated by the increasing documentation provided by satellite imagery. The thrust is two-fold: a better understanding of surface signatures of fronts will help not only in developing forecasting capabilities but also in inferring the situation under the sea surface that is unseen to the satellite.

In a first step, geostrophic dynamics of upper-ocean fronts are formulated. The newly established equations offer various advantages over previously used models. Fronts can be unidirectional (open outcrop line) or closed onto themselves (ring). A new solution has been discovered that describes the time evolution of elliptical warm-core rings. Good agreement with Gulf Stream rings validate the results. It is planned to exploit this solution to infer as much as possible about intense vortices in the ocean.

A parallel study of unidirectional fronts is aimed at understanding frontal waves, their stability, breaking and spin-off.

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James J. O'Brien, Principal Investigator

INDIAN OCEAN MODELLING

by Mark E. Luther and James J. O'Brien

We are developing a series of numerical models to describe the response of the Indian Ocean to observed winds stress patterns. The present version of the model is a nonlinear reduced gravity transport model, which covers the northwest Indian Ocean from 40°E to 74°E and from 10°S to 25°N. The model reproduces most of the observed features of the upper layer currents in this area, including the development and collapse of the two gyre system of the summer Somali Current, the associated propagation and coalescence of the cold upwelling wedges along the Somali coast, and the strong seasonal eddy activity along the Arabian coast. The model has shown that both the wind stress curl and its gradient are important in the generation of the two gyre system and the eddies along the Arabian Peninsula. The collapse of the two gyre system is found to be triggered remotely by a shift in the equatorial winds.

We are in the process of extending the model to include the entire Indian Ocean to the north of 25°S. This will enable us to better resolve the equatorial currents and the southern hemisphere currents, as well as allowing us to model the monsoonal flows in the Bay of Bengal and in the eastern Indian Ocean. The model is being used to develop a "now-casting" capability, using our most recent estimate of the winds from ships' reports. We will increase the vertical resolution of the model by adding dynamically active lower layers, so that we can study the deep countercurrents that are observed in many parts of the Indian Ocean. In the next version of the model, we will add more complicated physics, including thermodynamic and topographic effects in both the reduced gravity and multi-layer versions of the model. We will also use the reduced gravity model with a 25 year long wind data set to assess the importance of interannual variations in the wind driven currents of the Indian Ocean.

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Worth D. Nowlin, Jr.

Studies of the Stratification and Circulation of the South Atlantic

Our principal research goal is a better understanding of the general circulation of the South Atlantic. Several recent cruises (including the Long Lines section from Abidjan to Antarctica) have sufficiently expanded the historical data base of quality stations to complete such a study in the manner of Reid, Nowlin and Patzert (JPO, 1977) for the southwest Atlantic. As in that study, property distributions for selected core layers and isopycnal surfaces will be studied in conjunction with relative maxima in hydrostatic stability which coincide with vertical boundaries of the major water masses. Prior to the synthesis of the entire South Atlantic data base, we will publish vertical sections of properties from the Abidjan/Antarctica cruises.

Several ancillary studies will complement the description of the general circulation. Computer programs are under development to apply inverse techniques in the South Atlantic. This method will permit estimates of the absolute flow through the Long Lines section and other recent sections. For property interpretation of the results of the inverse analysis, regions of strong currents, or where current direction changes with depth must be better understood. The structure of the Antarctic Circumpolar Current at the Greenwich Meridian will be analyzed and compared to the frontal structure at Drake Passage from ISOS results. We will investigate the eastward extension of the Weddell-Scotia Confluence which separates the ACC from the Weddell Gyre. The flow in the southern Scotia Sea, including the westward-flowing Polar Slope Current, is poorly understood and will be further studied. A region critical to our understanding of the general circulation is in the southwest Atlantic where the northward-flowing Falkland Current and the deep western boundary current are in close proximity to the southward flowing Brazil Current and North Atlantic Deep Water. We will continue to investigate this region with particular emphasis on the connection between the Subantarctic Front at Drake Passage and the Falkland Current.

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DOREN NOF

MESOSCALE PROCESSES IN THE OCEAN

I. OBJECTIVES

The present contract focuses on two separate areas of research. One addresses the dynamics of isolated eddies and the other focuses on flows through channels and straits. Both studies are theoretical; models are developed with the aid of analytical or quasi-analytical models. The main objective is the development of nonlinear models for mesoscale processes such as Gulf Stream rings and shock waves in outflows.

II. MAJOR ACCOMPLISHMENTS

a. Dynamics of isolated eddies: i) Development of a model describing the behavior of "joint vortices," eastward propagating eddies and inertial Taylor columns. This model introduces a new concept in eddy dynamics -- the joint eddies. It has some similarity to the "Modon" because it consists of two eddies situated on top of each other in a three layer ocean. ii) Development of a model describing the oscillatory migration of deep ocean eddies. iii) Examination of the dynamics of elliptical rings and their clockwise rotation.

b. Strait dynamics: i) Determination of shock waves behavior in channels, currents and outflows. The purpose of this study is to examine the possibility that the abrupt and violent changes observed in many straits and outflows can be explained in terms of discontinuities (in the physical properties) which behave in an organized manner. ii) Examination of the flow through broad oceanic gaps. This study focuses on the cases where the gap influence on the flow in its vicinity is "catastrophic" in the sense that an entire current can be sucked into the gap even if the gap width is relatively small.

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Pearn P. Niiler

Direct Measurements of Circulation in Northeast Pacific Thermocline

Two subsurface moorings with nine VACM's on each mooring in and above the main thermocline were deployed in July 1982 at 42°N and 28°N along 152°W. In July, 1983, these were recovered with 18 full 12-month long records and in May, 1984, 18 full 10-month records were recovered. The third year deployment will be recovered in October, 1985. The principal scientific objectives of this study are to determine the low-frequency evolution of the temperature advection and geostrophic potential vorticity balance in the eastern North Pacific thermocline. Internal waves and circulation around the subpolar front are also measured. One instrument on each mooring was at 4000 m to also measure deep flow. The first two-year long records reveal a number of surprises. At 42°N, a "mean" flow to the east is apparent, while at 28°N the first year 1500 km progressive rector displacement to the southeast in one year is completely reversed next year to the northwest. Mesoscale eddy energy of 20-60 day period is not found at 42°N, so two"seasonal cycles" are apparent. At 28°N, the mesoscale is very energetic, vertically coherent over 4000 m and is of constant energy level between 800 and 4000 m. At 42°N, 70% of the kinetic energy in 10-40 day period band can be directly related to surface wind-stress curl via a barotropic Sverdrup balance (Niiler and Koblinsky, Science, 1985); in winter seasons, currents at 80 m depth are directly driven to the right of the wind. In winter of 1984, strong inertial motions are seen to propagate vertically through the upper 600 m of the 42°N mooring. A linear stability analysis of vertically spiraling mean geostrophic flows, as are implied by historical hygrographic data, reveal that the eastward shear at 42°N should be stabilized by the β -effect; at 28°N, the historical mean geostrophic current profile, however, would be unstable to growth of eddies. A general numerical theory of non-linear eddy growth in the mid-ocean is now being done, with the cooperation of NCAR.

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L.A. Mysak

LONG PERIOD WAVES AND CURRENTS

1. Wind stress and generation of annual Rossby waves.
The Rossby wave field generated by the annual cycle of the observed wind stress curl over the North Pacific Ocean has been obtained through numerical integration of the linearized reduced-gravity vorticity equation in spherical coordinates. The dominant source region of Rossby waves is adjacent to the eastern boundary between 20°N and 35°N. A second, less significant generation region has been identified over the central North Pacific between 35°N and 45°N from 150°W to 160°W. The remainder of the model domain exhibits mostly Ekman pumping of the pycnocline.

2. Trench wave generation by incident Rossby waves.
The response of a two-layer fluid in a coastal trench to the incidence of low-frequency Rossby waves from the open ocean has been determined. While both barotropic and baroclinic incident waves have been incorporated into the theory, the focus of the work has been on the nature of the response in the trench to first-mode baroclinic Rossby waves. We have shown that in both the Izu and Peru trenches, deep (lower-layer) longshore currents of O(5 cm s^{-1}) are generated by annual-period Rossby waves whose interfacial amplitude is 5 m. The longshore current speed is particularly large (up to 8 cm s^{-1}) when the longshore wave number (ℓ) and frequency (ω) of the incident wave are close to the complex (ℓ,ω) roots of the free trench-wave dispersion relation for a β-plane. In view of the published evidence (summarized in Magaard, JPO 1983) of annual-period Rossby waves in the vicinity of the Izu trench, it is conjectured that forced trench waves of the type described here may be detected in this trench from measurements of sub-thermocline currents.

3. Modon dynamics.
In the presence of a bottom Ekman boundary layer, an eastward travelling modon (vortex pair) slowly decays in amplitude and size. The analytical results for the stream function and vorticity behaviour are qualitatively similar to those found numerically by McWilliams et al (1981, DAO). For typical oceanic paramters, the decay takes place over a few months, with the modon travelling about 5 modon radii before complete dissipation. A study of the stability of modons has also recently been completed.

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PETER MULLER

DYNAMICS OF OCEANIC MOTIONS

This project aims at the understanding of the fundamental processes which govern the dynamics of small-scale oceanic motions. The work is basically of theoretical nature, including data analysis and numerical modelling. Two specific processes or phenomena are studied: small-scale vortical motions and the interaction between the surface mixed layer and interior motions.

Small-scale vortical motions

The vortical mode of motion carries the potential vorticity of the flow. At large and meso scales it represents the geostrophic and quasi-geostrophic flow. Vortical motion must also be expected to exist at small scales, in addition to internal waves which do not carry potential vorticity. The energy and shear content, the dominant space and time scales and the dynamics of small-scale vortical motions are not known. To develop a basic understanding of these motions and their role in oceanic processes this project analyses existing data sets for vortical motion, studies theoretically the interactions between vortical motions and internal gravity waves, and asseses the requirements for and the feasibility of an experiment which will unambiguously identify small-scale vortical motions in the ocean.

Interaction between the surface mixed layer and interior motions
(In collaboration with Dr. B. Garwood of NPS)

The long term goal of this project is to explore the prospects for the surface detection of interior motions. Interior motions interact with the surface mixed layer by a variety of complicated and not yet fully understood processes. To understand some of these processes and their observable surface signatures the project studies numerically the response of a bulk mixed layer model to prescribed interior velocity fields, representative of the large and synoptic scale variability of the ocean. Preliminary results indicate significant responses. The details depend sensitively on the time scale (and phase) of the interior motion with respect to the turbulent, entrainment and seasonal time scale of the mixed layer.

The project also participates in the development of an improved bulk mixed layer model which takes into account the rotation induced conversion of wind generated horizontal turbulent motion into vertical turbulent motion which entrains and mixes. This model predicts that mixing depends on the direction of the wind stress. A steady state version sucessfully reproduces the observed equilibrium mixed layer depth in the equatorial Pacific.

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CHRISTOPHER N.K. MOOERS

OPTOMA (OCEAN PREDICTION THROUGH OBSERVATION, MODELING, AND ANALYSIS) PROGRAM

OPTOMA, a joint NPS/Harvard program with participation by OSU and NOAA (NOS/PMEL), is taking the initial steps in real-time, four-dimensional data assimilation for the description and prediction of mesoscale variability in open ocean domains. The goals are (1) to determine the scientific limits of practical, open ocean mesoscale forecasting, and (2) to advance our understanding of the mesoscale kinematics, dynamics, and energetics in the California Current System (CCS). Over the past three years, quasi-synoptic surveys and ocean prediction experiments have been conducted in a 200 x 200 km domain (called NOCAL) centered about 200 km offshore from Point Arena (N. California) in the CCS. The basic scheme for 4-D data assimilation, called the Ocean Descriptive/Predictive System (ODPS), is based on an observing system plus statistical (objective analysis (OA)) and dynamical (quasi-geostrophic (QG)) models.

The kinematics of the CCS have been updated (Mooers and Robinson, SCIENCE, 1984 and Rienecker, et al., JGR, 1985). A new understanding of the CCS as a system of meandering turbulent jets, often close-packed cyclonic and anticyclonic synoptic/mesoscale eddies, and nearsurface thermal anomalies and fronts has emerged. This new understanding helps to interpret satellite imagery more fully and to infer cross-shore transport of properties over a few hundred kilometers in a week or so. The topics of local dynamics and energetics are in the early stages of study.

OPTOMA performed a prototype, real-time ocean prediction experiment (OPTOMA5) for a month in the summer of 1983 and a full, real-time ocean prediction experiment (OPTOMA11) for two months in the summer of 1984 in NOCAL. The results of the OPTOMA5 prediction experiment were very promising (Robinson, et al. NATURE, 1984), as are those from OPTOMA11. In OPTOMA5, mesoscale features evolved under the dominant influence of internal processes; in OPTOMA11, boundary conditions were most influential. These experiments involved shipboard quasi-synoptic surveys using XBT/CTD casts; an airborne synoptic survey using AXBTs; and satellite AVHRR imagery. The ODPS was used in real-time at NPS and Harvard. The OA model is used routinely at sea. The prediction experiments were supported by six airborne surveys and twenty shipboard surveys which provided additional information for model development and an improved description of the regional mesoscale field. Five more shipboard surveys and a few more airborne surveys are planned in FY85. In September 1984, OSU installed three current meter moorings, each with five current meters, which are due to be recovered from NOCAL in July 1985. Their primary purpose is to determine the mesoscale barotropic component of flow, and its relationship to the baroclinic component, in order to evaluate and modify our initialization procedure, as necessary.

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ROBERT N. MILLER

NUMERICAL MODELING OF SYNOPTIC SCALE OCEAN DYNAMICS

The principal objective of this work is the development of numerical modeling techniques for synoptic ocean forecasting and analysis. This includes numerical experiments and the investigation of theoretical questions that bear directly on the implementation of numerical models. Collaborative work with Dr. A. F. Bennett of the Institute of Ocean Sciences, Victoria, B.C. is directed toward settling the question of proper numerical implementation of open boundary simulations, i.e. those which model regions of ocean hundreds of kilometers in extent that lie far from shorelines. Solid progress toward understanding the nature of irregularities that arise in such simulations has been made and definitive results should be available by the end of calendar year 1985.

Simulation studies with the Harvard Open Ocean Model continue. Simulated data sets are being used in conjunction with numerical models(see Miller, Robinson and Haidvogel, J. Comp. Phys. 1983) and statistical models to determine quantitatively the nature of forecast errors. The natural extension of this work is the development of optimal estimation techniques for the combination of observed data with model forecasts. Optimal estimation techniques have been developed in the engineering community, but these techniques are too resource intensive to be practical for ocean forecasting purposes, and appropriate simplified versions must be found. A study in which optimal techniques were applied to simplified models is now complete(paper submitted, JPO). Findings from this study will be used to develop techniques for use with more sophisticated models. Careful attention is being paid to related developments in the meteorological community.

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M. S. McCartney

GENERAL CIRCULATION AND FORMATION OF WATER MASSES IN THE ATLANTIC OCEAN

The objective of this project is to increase our knowledge and understanding of the general circulation of the Atlantic Ocean. A main focus has been on the influence of subpolar deep convection on the water masses of the thermocline and the deep water. The tools used are traditional hydrographic ones: core layer and isopycnal analyses and dynamic computation of velocity fields. An additional powerful new tool is pycnostadal analysis: the use of potential vorticity distributions to infer sources and circulations of water masses. These tools are applied to both historical (Nansen bottle) station files and to modern CTD profile data. Studies currently near completion include the following: (1) the influence of convection west of Ireland on the thermocline of the North Atlantic subtropical gyre; (2) the abyssal circulation of the eastern North Atlantic Ocean; (3) the deep western boundary current of the tropical North Atlantic; (4) the transposed Antarctic Bottom Water of the western North Atlantic; (5) geostrophy in the abyss of the equatorial Atlantic; (6) a large deep anticyclonic eddy in the central South Atlantic (an Agulhas Retroflexion fragment); (7) the influence of subantarctic zone convection in the southwestern Pacific on the Antarctic Intermediate Water of the South Atlantic.

A set of four lines of CTD stations off the coasts of Brazil and Uruguay was collected in late 1984, at the beginning on the current contract period. Preliminary results are being included in (7) above. As calibration and editing of thee data proceed over the next few months, and the above studies are finished off, analysis emphasis will shift to this new data set (which will be combined with transects at 23°S and 11°S collected in 1983). Topics for study are the recirculation of the Brazil Current, the influence of the Falkland Current on the subtropical gyre, and the distributions of Intermediate and Deep Waters. Cooperative studies of the recirculation with A. Gordon and G. Roden are planned.

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Tony Maxworthy and
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TURBULENCE IN STRATIFIED AND/OR ROTATING FLUIDS

Our major effort over the past several years has been to characterize the structure of turbulent mixing on scales too small to be affected by the earth's rotation. We have performed a number of revealing experiments aimed at understanding how the vertical scales of motion are limited by a gravitational restoring force and how the resulting flattened, pancake-like eddies interact in the horizontal. In two experiments using oscillating and towed grids in a narrow stratified channel, we have observed the almost two-dimensional evolution of intrusions from the collapse of the initial 3-D turbulence. Discrepancies between the vertical scale of these intrusions and the predicted Osmidov scale has been attributed to 3-D effects and the competition for growth between adjacent fingers.

Extension of these experiments to a very wide tank has revealed that the flattened eddies which are formed by the collapse process interact strongly in the horizontal to produce vortex merging and a strong up-scale transfer of energy reminiscent of the proposed dynamical picture of (horizontally) two-dimensional turbulence. The physical mechanisms involved are also classified by these experiments and should result in an improved mathematical formulation of this problem.

Turbulent studies in a two-layer stratified flow tunnel are nearing completion. Among the more interesting results is the observation that the widely used Thorpe length scale (Phil. Trans. Roy. Soc., A286) does not always give a good indication of the active scales of turbulence. These and numerous other results are currently being written-up for publication.

A number of wave studies have been performed including: the formation of internal Kelvin waves by tidal flow over an obstacle in a narrow rotating channel (to appear in J.G.R.) and the absorption of wave energy at a critical level in a stratified shear flow. This latter study makes use of a unique shear flow facility and has shown that wave energy is absorbed into the mean flow before the waves reach the critical layer itself. Two completed papers have been published in J.F.M., 145 (1984) and J.G.R., 89 (1984) on wave generation in stratified and rotating and rotating-stratified fluids. A paper on wave propagation on vortex cores is to be published in J.F.M., 151 (1985).

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P. Malanotte-Rizzoli
G.R. Flierl

A Theoretical Study of Gulf Stream Instabilities, Eddy Production, Evolution and Interactions

We proposed to address important unresolved questions which have emerged from the experimental evidence accumulated in the past decade in the Gulf Stream and the regions of intense mesoscale activity on either side of the Stream (the Sargasso and Slope Water). We shall focus upon the theory of:

(1) The instability of the Gulf Stream and its relationship to the far field radiated waves in both linear and nonlinear stages.

(2) The possible formation of coherent eddies from strong radiation fields.

(3) The motion and evolution of detached or relatively isolated energetic features within the mesoscale eddy field.

(4) Interactions between strong eddies and eddies with currents.

Our approach will be a blend of analytical and computer simulation studies together with comparison when possible between our modelling results and the current data base of satellite imagery at M.I.T. This work will be done in collaboration with Prof. N.J. Zabusky who will be visiting M.I.T. for 3.5 months in 1984.

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P. MALANOTTE-RIZZOLI

GULF STREAM ACOUSTIC TOMOGRAPHY FEASIBILITY EXPERIMENT

Oceanic acoustic tomography has the promise of providing synoptic measurements of the three dimensional structure of the Gulf Stream, even in the swiftly moving surface layers where sound waves can penetrate along their paths between bottom-mounted instruments. Measurements of mass and heat flux, vorticity (using reciprocal transmission), the w-$\vec{K}$ spectrum of variability and the sound speed field itself are all candidates to be measured in future tomographic experiments. Tomographic measurements of basin scale variability will depend on measurements in the Gulf Stream. In the proposal we discuss some of the above scientific issues for which we expect to obtain zero-order answers.

A natural sequence of tomographic experiments in the Gulf Stream starts with a feasibility experiment which is proposed here. Acoustic transmissions, centered at 400 Hz and 100 Hz bandwidth between a bottom-mounted source and two bottom-mounted receivers at 20 km range on either side, will provide much information about the acoustic environment. In the proposed experimental layout, the ray angles at the surface and bottom are much steeper than those in previous tomographic experiments. A preliminary study of the modification to a steeper ray geometry is favorable. The experiment is proposed for the duration of a month in October 1984 near the bottom of the continental slope off Cape Hatteras in a region where the Gulf Stream is usually resident.

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LORENZ MAGAARD

ANALYTICAL MODELING OF LOW-FREQUENCY PROCESSES IN THE NORTH PACIFIC

The objective of this program is to complete our studies of low-frequency processes at the surface and in the interior of the North Pacific Ocean based on long-term historical and computer-simulated temperature (or geostrophic stream function) records.

In our analysis of the TRANSPAC data (White and Bernstein, JPO, 1979, 592-606) we now concentrate on the highly energetic fluctuations in the western half of the North Pacific. We have shown that these fluctuations are not manifestations of neutrally stable Rossby waves. We are trying to explain these fluctuations by local baroclinic instability or radiating instability (Talley, JPO, 1983, 2161-2181) of the non-zonal mean flow.

The other oceanic data under consideration (obtained from Dr. S. Tabata, IOS, Sidney, B.C.) are the 25-year series of isopycnal displacements at OWS Papa (50 N, 145 W) and along line P (connecting OWS P and the coast at about 48.5 N, 125.5 W). The displacements show high energy in the 6-8 year period range. We test the hypothesis that the anomalously warm water of the west coast of North America, associated with each El Nino event, triggers the slow westward propagation of long first mode basoclinic Rossby waves that might manifest themselves in the isopycnal displacements.

Besides our studies of oceanic data we are working on two computer-simulated data sets from a region simulating a portion of the MODE area (obtained from Dr. A. Robinson, Harvard) and from the North Pacific (0 -65 N, 145 E-125 W, obtained from Dr. R. Haney, NPS). We are analyzing these data sets with respect to Rossby waves with the idea to study their generation and predictibility.

We have completed our analytical studies on the generation of Rossby wave driven secondary flows along the Hawaiian Ridge (Mysak and Magaard, JPO, 1983, 1716-1725; Oh and Magaard, JPO, 1984, 1510-1513). There is some observational evidence that the predicted current (North Hawaiian Ridge Current) actually exists. We are planning to pursue this question further by numerical studies and field work.

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DONALD B. OLSON

THEORY AND OBSERVATION OF OCEAN FRONTAL ZONES

Research in the past year has focused on studies of the interaction between mesoscale eddies and the gyre scale circulation in the South Atlantic and Indian Oceans. As part of this effort a two-layer diagnostic model to estimate the mean dynamic height, eddy energy, and potential vorticity fields in these oceans from observations of thermocline depth has been constructed. The results have been used to estimate the distribution of eddy energy relative to the circulation in these basins from historical data as well as for calculating the internal structure of rings from the Agulhas and Brazil currents with synoptic data. Drifter velocities from a deployment west of the Agulhas retroflection in late 1983 (five units) and in the Brazil Current in late 1984 (ten units) are being used to augment the results from hydrographic data with measured velocities. The results to date include tracking and mapping of four rings with hydrographic (A. Gordon), satellite sea surface temperature (O. Brown and R. Evans), and the drifter data. Five other eddies have been covered by a combination of two of these three types of observation. An additional drifter deployment in the Agulhas will take place in February 1985 (five units) in cooperation with J. Luyten and J. Toole. The results of the 1983 Agulhas work shows these rings to be the most energetic rings in the world ocean. Comparison between the energy flux into the South Atlantic due to these features and the energetics of the basin show they are a significant energy source for the gyre. A comparison between Gulf Stream, Agulhas, and Brazil Current rings is currently underway. Analysis of water mass modification and fluxes relative to the rings are being carried out in coordination with R. Fine and A. Gordon. Analysis of the longer term drifter data in relation to the distribution of mean current features, eddies, and inertial motion in the surface layer are currently underway. Results to date have isolated a coherent large scale flow relatively devoid of eddies extending from the southern Bengula region out into the center of the South Atlantic along 20°S. Details of a tight recirculation region associated with the Brazil Current are appearing in the drifter trajectories from the Fall 1984 deployments. This data is complemented by hydrographic sections across the recirculation by A. Gordon and M. McCartney.

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Thomas R. Osborn

Turbulence Measurements from USS Dolphin

The submarine Dolphin has been instrumented to measure velocity and temperature microstructure along horizontal transects. Information about the mean shear (with a Doppler acoustic profiler) and the density field (from a CTD) is also collected. The field work in October 1984 included acoustic scattering measurements by Farmer's group from IOS, Pat Bay and biological sampling by Haury of SIO. There has been a steady expansion and modification of the instrumentation suite.

The project was begun to study the role of turbulence and organized structures in the upper layer and thermocline. Experience has shown that the system is also able to quantify the relative importance of turbulence and salt fingers.

The horizontal motion of the submarine allows detection of salt fingers. Measurements have revealed fingers at values of R as large as 8, with fingers frequently seen at values between 4 and 6. These values of R are well removed from the region of fastest growth. Salt fingers appear to be an ubiquitous feature when the local temperature and salinity fields are appropriate.

We have examined the statistics of 2600 dissipation estimates from a turbulent upper layer. The distribution of the dissipation is not log-normal due to an excess of small values and a deficit of large values. Using the log-normal fit to estimate the mean and standard deviation of the sample overestimates both parameters.

The effect of stratification on turbulence reported by Gargett, Osborn and Nasmyth (JFM 1984) has also been observed in these data.

We believe the fall 1984 data include the generation of an inertial event by the wind and that analysis will show the turbulence related to the shear of that feature.

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W. B. OWENS
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LARGE-SCALE CIRCULATION: DEEP NORTHERN-BOUNDARY CURRENTS IN THE NORTH PACIFIC

We are attempting to describe the deep northern-boundary currents of the North Pacific on the basis of observations made during 1981-82: a line of year-long current measurements extending southward from the Aleutian Islands along Long. 175°W, and CTD sections extending southward from the Aleutians along Longs. 165°W, 175°W, and 175°E. One current flows westward along the Aleutian Island Arc and appears to be the recirculation boundary current required by deep-circulation theory. The other, lying immediately to the south, flows eastward, and appears to be a concentration of interior flow forced at least in part by the topography of the Aleutian Rise.

At Longs. 165°W and 175°W the recirculation current is a proper boundary current, lying along the flank of the Aleutian Island Arc, but at Long. 175°E, it is separated from the boundary by about 100 km. Analytical modeling suggests that this separation is due to the change in orientation of the Island Arc, which trends ENE-WSW east of Long. 180°, but WNW-ESE west of 180°.

A preliminary report on our results was published in 1985 in Progress in Oceanography, Vol. 14. Work is in progress on a full account of the project.

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CLAYTON A. PAULSON

ARCTIC INTERNAL WAVES

As a part of the Arctic Internal Wave Experiment (AIWEX), we will make velocity measurements with current meters suspended from the ice. The experiment will be conducted in spring 1985 about 200 nautical miles north of Prudhoe Bay. The objectives of our participation are: 1) to determine the spectrum of internal waves vs. depth in the upper 500 m, 2) to compare observed spectra with the Garrett-Munk model, 3) to investigate the isotropy of internal waves and 4) to cooperate in an investigation of the structure and energetics of the 10 to 20 km diameter eddies which are common in the Canadian Basin. Six current meters will be distributed from 100 to 500 m depth at a central site. Three additional meters will be moored at 150 m depth in a triangular array surrounding the central site.

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CLAYTON A. PAULSON

AIR-SEA INTERACTION

Our current research is centered around the use of a towed thermistor chain to obtain observations of the thermal structure of the upper ocean. The general objective is to improve our understanding of the dynamics of mixed layers, internal waves and fronts.

As a part of the Mixed Layer Dynamics Experiment (MILDEX), we towed the thermistor chain for a distance of about 1,000 nautical miles in various patterns in the MILDEX area approximately 300 mi. west of Monterey, California. These data are being analyzed to determine: 1) spatial variation of the thermal structure of the upper 100 m, 2) wavenumber properties of the internal wave field and 3) the structure of a front which was surveyed on the return to San Diego. The data are being analyzed in cooperation with other MILDEX investigators, particularly Lloyd Regier of Scripps Institution who measured vertical profiles of horizontal velocity with an acoustic doppler velocimeter.

We have begun work on a summary of our towed observations of internal waves including those from MILDEX. The tows on which the summary is based total several thousand miles in both the North Pacific and the North Atlantic. We will compare wavenumber spectra of isotherm displacement with other observations and with the Garrett-Munk model. The vertical coherence of internal waves will be summarized and the evidence for isotrophy will be examined.

We have completed a manuscript on the analysis and modeling of the internal tide. The tide was observed by moored and towed thermistor chains in Rockall Channel west of Scotland. It was shown that the internal tide was generated by the interaction of the surface tide with Rockall Bank, about 200 km away from the location of the observations. There is good agreement between the observations and a model for the generation of the internal tide at a step-like shelf.

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Robert Pinkel

Upper Ocean Physics Program FY85

Efforts in this program center on the analysis of data sets obtained from FLIP during May 1980 and October-November 1983 (MILDEX). The information obtained consists of extended series of CTD profiles to 400 m in 1980, 320 m in 1983 and multiple Doppler sonar velocity profiles. The CTD data are used to infer the vertical velocity field in the sea, while the sonars sense a 45° slant component velocity. In 1980, the two types of motion could not be consistently related using linear internal wave theory. Subtle but significant discrepancies are seen at high vertical wavenumber and high frequency which suggest the presence of nonlinear and perhaps non-internal wave data in the measurements. The 1983 data look superficially quite different than the 1980 measurements. A detailed statistical analysis is in progress. The 1983 sonar measurements will also provide a more precise picture of the directional aspects of wave propagation than the previous work. Subsequent analysis effort will be centered on the directionality issue.

Associated with the data analysis effort are several engineering tasks. The first is to improve the range and reliability of the FLIP sonars. This is being effected through improvements to the receive electronics. Ranges of order 2.25 km have been achieved in preliminary tests. The second engineering effort explores design concepts for a small scale, coherent Doppler sonar system. This will have meter scale range resolution and be able to investigate the small scale shear field. The final technical task is to convert a commercial 150 kHz Doppler sonar from 110 V power to a battery powered self contained configuration, for use from a conventional mooring. Tests on this system will be conducted during summer and fall 1985, in preparation for the January 1986 FASINEX experiment.

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Robert Pinkel

Acoustic Velocity Profiling of the Arctic Internal Wavefield

In spring 1985 an internal wave observational effort, AIWEX, is planned for the Arctic Ocean. Arctic measurements are of first order importance because:

1) Energy levels in the wavefield are known to be lower than at midlatitude. A clue to the energy regulating mechanism of the wavefield might be found.

2) Momentum transport from the winds to the ice cover to the upper ocean can be measured. The response of the wavefield to known forcing and the role of the wavefield in transporting momentum can be qualified.

In conjunction with AIWEX we will operate a four beam acoustic velocity profiler in the Arctic. The system is an improved equivalent of that found on many research ships today, purchased from RD Instruments Incorporated, San Diego. Expected range of the sonar is 200 - 400 m depending on scattering levels in the water. Previous Arctic acoustic measurements (Holliday, pers, comm.) suggest that scattering will be strong. The sonar operates at 150 kHz. Slant velocity profiles will be recorded independently from each of the four beams. Range resolution is of order 3-8 m. Scattering strength (uncalibrated) will also be recorded, to give some index of the depth-time variability of Arctic volume reverberation. These data, as well as sonar tilt and azimuth, will be combined with AIWEX wind, ice motion, and CTD studies, to complete the observations. Data analysis efforts will occupy the remainder of FY85 and 1986.

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Joseph L. Reid

WORLD OCEAN CIRCULATION

During the first part of the FY85 - FY86 period I have completed the study of the total geostrophic circulation of the South Pacific Ocean. The paper was given, at the fall AGU meetings in San Francisco, and the abstract. The full manuscript is being submitted to Progress in Oceanography.

The study of the Norwegian-Greenland Sea (with Jim Swift), whose preliminary results were reported by abstract (Reid, 1982; Swift, 1982) is nearing completion. It is based upon the expedition carried out successfully in February-April 1982, aboard the C.S.S. Hudson, in cooperation with the Bedford Institute of Oceanography. The data obtained on this expedition (supported by ONR) are beyond question the best and most complete data set yet taken, and allow a much more precise judgement about the differences in the deep characteristics of the various basins and the lateral extensions of the shallower layers. One item is of particular note: the densest abyssal water passing southward from the Arctic Ocean, on the westward side of the Fram Strait between Spitsbergen and Greenland, appears to be slightly warmer and more saline that the densest waters that enter the Arctic Ocean near Spitsbergen. While this has been proposed before, no data of such high quality have been obtained to evaluate the differences. The increase in heat and salt content must be a consequence of some form of vertical exchange that has taken place within the Arctic Ocean.

I have made substantial progress on a study of the total geostrophic circulation of the South Atlantic Ocean from Antarctica to the equator, along the lines of the South Pacific study. The various tracers (temperature, salinity, oxygen, nutrients, freon, helium-3, and to some extent the carbon 14) leave patterns (e.g., Reid, Nowlin and Patzert, 1977) that can be used to estimate the sense of flow and the large-scale trajectories of the waters. With these in hand, the relative geostrophic flow patterns can be augmented with barotropic components in accord with the tracer patterns, and a total geostrophic flow field can be calculated.

The South Atlantic Ocean is, in principle, the best area for this sort of study, as it is the cross-roads of so many distinct layers of water, with different sources and different characteristics. Beneath the upper layer, these include the intermediate layer of low-salinity, high-oxygen water from the south, the low-oxygen high-nutrient Upper Circumpolar water from the Antarctic, the several layers of high-salinity, high-oxygen high nutrient content from the Antarctic Circumpolar water, and the denser, less saline but colder water from the Weddell Sea, with higher oxygen and lower nutrient content. Over a substantial depth range and area there is an input of waters from the Indian Ocean entering from south of Africa, with their own separate identity.

Each of these layers has its own pattern of characteristics, from which a sense of flow can be estimated, and a barotropic component determined. These layers do not all extend everywhere in the South Atlantic, but there are large-area overlaps that allow the barotropic components to be evaluated at more than one depth, and thus fairly well constrained.

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UPPER OCEAN DYNAMICS

MODELLING

A theory of a two-dimensional wind-driven diabatic ocean mixed layer with strong horizontal gradients has been formulated analytically. An equation that allows the relaxation of a strict Ekman balance--Coriolis force against wind stress--is derived from careful consideration of the cross-gradient momentum balance. The relaxation scale depends implicitly on the mixed depth and density distributions which are determined by mixing and diabatic processes. When the density contrast at the base of the mixed layer becomes small, the relaxation scale becomes small and high gradient front-like features can appear in the mixed layer. These fronts are then advected around in the mixed layer.

Initially, this model was applied to the situation of coastal upwelling in a two layer ocean. A front rapidly forms between the dense upwelled water and light offshore water. This front is advected offshore and modified by further entrainment of lower layer water and surface heating. This model has been generalized to a many layer ocean where the oceanic interior flow (lower layers) is governed by potential vorticity conservation. An important feature of this model is its capacity to bring deeper layer interfaces (analogous to isopycnal surfaces) up to the mixed layer base and outcrop these density surfaces at the ocean surface. In addition, internal-inertial wave dynamics has been added to the model. A series of model runs are being performed to examine the response of the upper ocean to wind stress and wind stress curl and the coupling of the mixed layer to the ocean's interior flow.

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UPPER OCEAN DYNAMICS

MIXED LAYER DYNAMICS EXPERIMENT (MILDEX)

A freely drifting buoy, called the Current Meter Drifter (CMD), was deployed for 18 days between 25 October and 11 November 1983 during the Mixed Layer Dynamics Experiment. The CMD supported 15 Vector Measuring Current Meters (VMCMs) distributed down to 141 m, 5 Aanderaa thermistor chains down to 800 m and a telemetering surface meteorological and LORAN C position location package. Concurrently, R/P FLIP was deployed in the area and Dr. R. Weller (WHOI) was making current profiling measurements. The winds were generally light during the experiment with speeds less than 5 m/s except during the passage of two warm fronts on 28 October to 1 November and 7 November to 11 November. In the later frontal passage, the wind speeds exceeded 15 m/s. Under the light winds, strong surface heating occurred with an average surface heat flux into the water of 82 W/m^2. The CMD drifted to the ENE with an average speed of 4.5 cm/s. The drift of FLIP was similar, although faster, for the first part of the experiment and then the two platforms diverged strikingly. During the light winds and strong heating period, the upper ocean is dominated by diurnal cycling with significant coherence in both velocity and temperature between the CMD and FLIP.

During MILDEX, the heat content of the upper 50 m at the buoy is nearly constant and does not reflect the observed surface warming. When the heat content is corrected for changes due to the physical motion of the buoy in a spatially varying thermal field and for relative advection of water past the buoy, the change in observed heat content compares well with the cumulative effects of surface heating. A one dimensional heat budget for the upper ocean is completely unsuccessful. The experimental site, although well offshore, is influenced by eddies in the California Current system and these eddies transport heat horizontally in the upper ocean. Work is continuing on modelling this transport and calculation of the corresponding momentum budget.

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Allan R. Robinson

DYNAMICS OF OCEAN MOTIONS

This contract continues research on the dynamics of oceanic motions: the theory and modelling of fundamental dynamical and energetic processes in the sea and their interactions, and the relationship of theory and modelling to the interpretation, analysis and design of observational data and experiments. Our interests lie primarily in the dynamics and the forecasting of low frequency variability of ocean currents (mid-ocean eddies and intense current systems), the mid-latitude general circulation, and in near surface layer/deep current interactions. Our modelling research is directed toward studies of the local dynamics of open regions of the ocean, (i.e. arbitrary regions which flow across their boundaries), and the relationship of the larger scale general circulation in which it is embedded. Central to our research philosophy is the Descriptive Predictive System (DPS) concept. The system components are a dynamical model, a statistical model and an observational network. The output of the system is "optimal" field estimation (past, present and/or future). For practical nowcasts and forecasts these fields can most efficiently exploit available data resources. For scientific purposes, these fields form the best basis for regional process studies, specifically carried out by open regional vorticity and energy dynamical analyses. A major thrust of our present and proposed research is the real time operation of the DPS. A first successful real time forecast predicted an eddy merger event in the California Current System (Robinson et al, Nature 1984). We now have the capability of running the dynamical model on shipboard computers which is of essential for the development and verification of real time forecasting schemes. Moreover, the strictly scientific purposes, real time forecasts and dynamical interpolation reveal subregions of most active physics which can guide in real time the evolution of experimental sampling strategy.

Research in progress includes dynamical model developments to deal with effects of mixed layers, coasts, islands and sea mounts. Primitive equation experiments are being undertaken to be used where needed and to compare with quasigeostrophic results. EOF and multiple time and space scale objective analyses for intense current and jet regions are used for California Current and Gulf Stream studies. The DPS has now been set up for use in the latter region for application to ring and meander dynamic studies as well as for nowcasting and forecasting.

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GUNNAR I. RODEN

MESOSCALE FRONTS OF THE SOUTHERN OCEANS

Research focused on thermohaline fronts of the western South Atlantic as part of the cooperative Southern Oceans Program. The Brazil current extension front and the subantarctic front were investigated successfully in a 23 day field experiment in November 1984, which was coordinated with field experimants by Arnold Gordon and Michael McCartney in adjacent areas.

The mesoscale fronts experiment was carried out in the central part of the Argentine basin and had as its objective to study the threedimensional thermohaline structure and depth penetration of two major fronts in the western South Atlantic. A total of 101 CTD stations were made and 178 XBT's were deployed. Preliminary findings indicate that both fronts are well developed and have deep signatures. The Brazil current extension front extends in a SW - NE direction between latitudes 40 and 37 S and is marked by strong temperature, salinity and density gradients, which penetrate to 1000 m. The subantarctic front is oriented in a predominantly east-west direction between latitudes 41 and 42 S and is characterized by large horizontal temperature and salinity gradients in the upper 300 m. In the upper 100 m, these gradients balance each other in such a way, that the resulting horizontal density gradients are small. The region between the Brazil current extension and the subantarctic fronts is noted for numerous large eddies. Baroclinic flow associated with the Brazil current extension extends to the bottom, near 5000 m. Baroclinic flow associated with the subantarctic front is recognizable to about 3000 m.

Two satellite tracked drifters, released by A. Gordon farther to the west transited the working area of the mesoscale frontal experiment in the central part of the Argentine basin. One of the drifters moved from SW to NE near the Brazil current extension front, the other moved in an easterly direction just north of the subantarctic front.

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THOMAS ROSSBY

STUDIES OF FRONTAL MIXING IN THE GULF STREAM

This is a joint Norwegian-American program to study cross-frontal processes at a selected number of sites along the cyclonic edge of the Gulf Stream. The field program is scheduled to take place this fall on the Norwegian research vessel Hakon Mosby from the University of Bergen.

Preparations are progressing satisfactorily. The first trials with the towed CTD fish "Sea Soar" went very well. Additional tests are scheduled throughout the spring and a major "dress rehearsal" is planned for early June.

Mr. John Lillibridge from URI visited the University of Bergen to help streamline the processing software. The main task ahead now is to integrate the navigation data into the CTDO, data streams. This should be fairly straightforward and will be tested in June.

Purchase of the Sippican XCP system will be done shortly, as well as of other materials for the field program. Since funding has been obtained for FY85 and the budget for FY86 has already been submitted ($92,290), no further requests are made now. Modest funding may be requested for FY87 to finish the analyses.

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THOMAS ROSSBY

STUDIES OF THE STRUCTURE AND TRANSPORT OF THE GULF STREAM AT 73°W

Between September 1980 and May 1983 sixteen sections of temperature and velocity were obtained using the Pegasus instrument along a transect across the Gulf Stream at 73°W. These data are now the subject of several studies. These are:

"The Structure and Transport of the Gulf Stream at 73°W". M.S. thesis by Daniel Halkin. Paper by D. Halkin and T. Rossby submitted to the Journal of Physical Oceanography.

"A Test of Geostrophy in the Gulf Stream". Part of Ph.D. thesis by Elizabeth Johns. Finished. Paper in preparation.

"The Heat Transport by Ocean Currents across 32°N Latitude in the North Atlantic Ocean". Master's thesis in progress by T. Rago. This study is very similar to the Bryden and Hall study except that it uses absolute velocity data from Pegasus (and certain moored current meter records) to determine all of the western boundary fluxes. This study will also try to estimate the magnitude of the seasonal cycle of the meridional heat flux.

"The Eddy Energetics of the Gulf Stream". Studies by the Principal Investigator while on sabbatical at the University of Bergen, Norway.

"A Comparison of the Potential Vorticity Fields across the Gulf Stream in the Florida Straits and at 73°W". A joint effort between Prof. K. Leaman at the University of Miami and the Principal Investigator. A preliminary report was given at the Spring AGU meeting in Cincinnati, May, 1984.

A final data report of the Pegasus data is in preparation. No further funds will be requested for this program.

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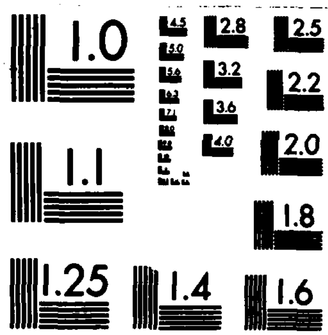

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Thomas Rossby & Everett Carter, Sr.

LAGRANGIAN STUDIES OF THE GULF STREAM USING RAFOS FLOATS

The objective of this program is to study the Lagrangian properties of fluid motion in the Gulf Stream using a new class of passively controlled isopycnal Swallow floats called "Rafos" floats. By repeatedly seeding the Stream with these floats we can examine

1) the space-time properties of the path of the current,
2) the three-dimensional velocity field and its coupling to the path structure,
3) pathways of fluid exchange with the surrounding waters, and
4) stirring and mixing processes.

These data will be used to study the energetics, dynamics and dispersive properties of the Gulf Stream. Close cooperation is planned with the numerical modelling and simulation efforts of Prof. A. Robinson and his group at Harvard University and with Dr. Dale Haidvogel at NCAR.

The field program is underway. Three sound sources for acoustic navigation have been established. After some initial difficulties with ballasting we have obtained eight 30 day trajectories starting at Cape Hatterass. Starting this January, floats are being launched from a commercial freighter. The initial results are consistent with the premise that there is a high likelihood that floats will remain trapped in the Stream for appreciable distances. Indeed, of the eight tracks, two floats escaped after about 500 km, one was trapped in a cold core ring and the remaining five travelled at least 1500 km before leaving the current. The essential point here is that as long as the basic two-dimensional structure of the current is not upset, floats and hence water will stream along in the current without exchange or loss to the sides. A preliminary report has been prepared for publication in the Bulletin of the American Meteorological Society.

As the data base grows, we will be able to study these processes in detail. The work will benefit greatly by collaborating with Prof. R. Watts and his studies using inverted echo sounders, with Prof. P. Cornillon and his remote sensing studies of the Gulf Stream region (very powerful synoptic interaction of the region surrounding the current), and with the numerical modelling studies at Harvard and NCAR.

We expect this program to play a significant role in upcoming studies of the Gulf Stream system in 1986 and 1987. We would like to put growing emphasis on the interactions between the Stream and the surrounding waters. If, as is expected, there will be major Gulf Stream programs, we anticipate that arrays of floats will be used to study these in detail. We plan to submit a proposal later this year. The cost, per annum, to sustain a significant "Rafos" field program will be in the 300-400 k$ range depending mostly on sound source requirements.

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David M. Rubenstein

DYNAMICAL COUPLING BETWEEN THE OCEAN MIXED LAYER AND UPPER THERMOCLINE

An increasing body of evidence points toward strong coupling mechanisms between the ocean mixed layer and the thermocline. These mechanisms involve mixed layer entrainment, inertial wave intermittence, exchange of momentum and buoyancy, and various mixing processes. Spatial variability, background vorticity, and density fronts can affect dynamics in both the surface layer and the ocean interior. My objective is to elucidate some of these mechanisms, using a modeling approach, with guidance from some recent observations.

During this first year, I have developed a new two-dimensional model of ocean dynamics. A vertically homogeneous mixed layer is described by a set of slab equations, and is driven by varying surface fluxes of momentum and buoyancy. Beneath the surface layer, a turbulence free, stratified interior layer responds to inertial (vertical) pumping. Near-inertial internal waves are generated, and are able to propagate into the ocean interior. Entrainment allows the mixed layer to deepen and entrain momentum and heat after passage of a storm.

I have applied this model to examine the effects of ocean fronts on the variability of near-inertial motions. The results suggest that the mean vorticity associated with a front acts to generate inertial motions over length scales comparable to the frontal width, or smaller. Inertial pumping generates internal waves that propagate downward and away from the front. Radiation damping acts selectively to dissipate near-inertial energy in the front and its vicinity. In the thermocline, the scattering of internal waves produces a wave-like modulation of the amplitude of near-inertial motions.

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Richard L. Salmon
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Analytical and Numerical Studies of Flow Over Ocean Bottom-Topography

Statistical theories of flow over topography predict that even turbulent flows have on average a "static" component locked to the topography. The significance of this contour flow in oceanographic flows is investigated through a series of numerical simulations of one and two-layer flow. The model topography used in these numerical experiments ranges from highly idealized geometrical forms to accurate representations of actual oceanographic structures including seamount chains and continental shelves. The flows in these simulations are driven in a variety of ways including turbulent decay, dynamically interactive large-scale cross currents, and surface winds. The relationship between the strength of the driving and the amplitude of the resultant component of contour flow is sought, with particular attention being paid to the possibility of multiple equilibria. The numerical experiments are compared with the predictions of statistical equilibrium theory, and to nonequilibrium approximations for the evolution of the energy spectrum and the autocorrelation of velocity at different times. Also these statistical approximations are to be used in a parameterization to improve the quality of the simulations.

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Thomas B. Sanford

OCEAN VARIABILITY AND DYNAMICS

The significance of inertial wave/mean flow interactions has been demonstrated with our observations and theoretical studies (Kunze and Sanford, JPO 1984; Kunze, JPO in press). When an inertial wave moves into a region of greater vorticity, its amplitude increases and wavelength shortens. These changes lead to shear instability and mixing. This insight provides an important framework for understanding the structure and variability of inertial waves and oceanic mixing. In December 1983 we executed an experiment in a Gulf Stream cold core ring to confirm the enhancement of inertial waves propagating toward more positive vorticity. This is one of the few examples where upward going inertial waves are more energetic than the downward going ones. Eric Kunze will be presenting a Ph.D. dissertation this summer based on the observations in fronts and rings and his theoretical and numerical studies.

Classic EM measurements initiated under ONR support 15 years ago have been shown to provide accurate determinations of Florida Current transports (Larson and Sanford, SCIENCE 1985). Other subcables are being examined in regions of strong flow or severe observing conditions.

David Lai has found that EMVP and current meter measurements taken several days after the passage of a hurricane at Site D reveal energetic near-inertial motions which extend from the surface to the ocean bottom. These motions propagate downwards and seawards and are dominated by the lowest three dynamical modes on a sloping bottom. It appears that these motions result from reflections of inertial waves from the continental slope or from the actual interaction of the hurricane with the slope. Another part of the research is a comparison of velocity shear spectra at different locations. The aim is to investigate the validity of a "universal" shear spectrum and conditions under which universality breaks down. It is found that the shear spectra in the Norwegian Sea deviate significantly from those in the Sargasso Sea, the latter being representative of the Gargett, et al. "universal" spectrum. The buoyancy frequency in the Norwegian Sea is about one-third of that in the Sargasso Sea. It appears that the buoyancy frequency affects the shear spectrum in a more complicated way than just the WKB-stretching and normalization of the velocity data, probably via the existence of a critical Richardson number.

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THE DEVELOPMENT OF A FINE- AND MICROSTRUCTURE PROFILER

A freely-falling profiler is being developed which will measure fine-scale variations in density and horizontal velocity over the full ocean depth and micro-scale variations in temperature, conductivity, index of refraction and velocity over a more limited depth range. The data are recorded internally on solid state memory so that the pressure case need not be opened between dives. The fine-scale sensors include a CTD, acoustic travel-time current meters to sense flow relative to the vehicle, accelerometers to measure vehicle response, and acoustic gear to obtain the absolute velocity of the vehicle. The microstructure sensors include vertically oriented fast response conductivity and temperature probes, two horizontally oriented fast response conductivity probes mounted on rotating wings, and a removable optical shadowgraph system (being developed with NSF funds). In the near future we plan to add shear probes for resolution of the smallest scales of variability in velocity.

The great advantage in combining fine- and microstructure measurements in one instrument lies in its ability to test fundamental ideas about how mixing occurs in the ocean. Attempts to compare data from separate instruments have largely failed in the past. This instrument will measure the appropriate hydrodynamic stability parameters (Richardson Number and density ratio) on the fine-scale and allow direct comparison with the observed forms and intensity of mixing events. The first use of the instrument will be during the C-SALT (Caribbean-Sheets and Layers Transects) cruise in November, 1985, which is a study of a strong salt fingering system. It will also be deployed in an upper ocean front during the Frontal Air-Sea Interaction Experiment (FASINEX). Future plans include a study of deep ocean mixing and examination of the mixing associated with recently ventilated thermocline waters.

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William J. Schmitz, Jr.

LOW-FREQUENCY OCEAN CIRCULATION

The main goal of this project and of the principal investigator is to describe the properties of the low-frequency ocean circulation, with particular emphasis on the relation between eddies and mean flow. A secondary objective is a comparison of the data base with results from numerical models.

Several long-term deployments of arrays of moored instruments in the North Atlantic were completed by 1977 and a similar geographical exploration of the North Pacific was initiated in 1980. Two principal results from an array deployed along 152E from 28 to 41N during 1980-1982 are: (a) estimates of abyssal eddy kinetic energies in the western North Pacific that are much lower than found in the western North Atlantic; (b) a vertical distribution of eddy kinetic energy that is nearly the same baroclinically in both oceans in their mid-latitude jets.

Model-data intercomparisons were started with regional numerical experiments in 1978 and expanded to gyre-scale runs in idealized geometry beginning in 1979. The regional numerical model available tended to do a decent job in the MODE area for the period range (nominal) of 50 to 150 days, but not otherwise. The gyre-scale eddy-resolving models developed by W. R. Holland at NCAR tended to reproduce approximately many of the observed features of the North Atlantic eddy field, with the main question becoming the zonal penetration scale from the west coast.

A major new array deployment in the western North Pacific began in the fall of 1983, extending coverage zonally from 152E across the North Pacific at mid-latitudes. The main priority of this project is and will be publication on the new North Pacific data base, including comparisons with the North Atlantic. A new wave of intercomparison of observation with Holland's models was initiated in 1984. The zonal scale question was resolved, and eight-layer runs are now being examined.

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Friedrich Schott

Western Boundary Current in the Tropical and Subtropical Indian Ocean

A combined program of shipboard and moored measurements is carried out east and north of Madagascar and off Somalia with the main objective to measure the variations at seasonal and shorter periods of the boundary current transports under the effect of the reversing monsoon winds. A total of 10 moorings are deployed during October 1984 - October 1985 (3 at 23°S in the East Madagascar Current, 3 off the northern tip of Madagascar, 4 across the Somali Current at the equator). The Somali Current array will be redeployed for a second year in September 1985, including two self contained upward-looking Doppler current profilers to measure the near-surface current structure. Shipboard measurements are carried out with the French R/V "Marion Dufresne" using the Ametek DCP4400/115 kHz Doppler current profiler which we installed in that vessel, as well as CTD/XBT and surface thermosalinograph measurements. During the first cruise in October 1984, good transport measurements were obtained in the Somali Current, indicating that the cross equatorial Somali Current (12 Sv in the upper 100 m) turned eastward south of 2°N and that a northern gyre existed between 6° and 12°N (carrying 32 Sv in the top 200 m) which was unconnected to the cross equatorial flow. During that cruise, sections with current profiler and XBT's were also taken at several latitudes over the East Madagascar Current which had core speeds of more than 1 m/s. The current there was found to be more barotropic than the Somali Current (i.e. much of the transport is below the range of the Doppler profiler) and transport estimate calculations are still in progress combining velocity profiler and XBT data. An extensive survey is to be carried out in April 1985 to study the current patterns during the spring transition before the onset of the summer monsoon.

Besides the moored current meter stations, subsurface pressure recorders were installed at various locations with the intent to calibrate sealevel differences with moored transport measurements as a basis for evaluation of longer-term sea level measurements in the future.

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A STUDY OF THE EFFECTS OF EL NIÑO IN THE CALIFORNIA CURRENT

Eight 3-day cruises were conducted from March 1983 - December 1983, to monitor the California Current during the 1982-83 "El Niño-like" event. These data, coupled with data taken by the CalCOFI program during early 1983 and throughout 1984, provided a 20-month-long time series which monitored the onset, development and decline of the 1982-83 mid-latitude event.

The large-scale structure of the California Current during the 1982-83 mid-latitude North Pacific "El Niño" event showed several persistent (>16 months), anomalous conditions: positive sea surface temperature anomalies (1-2.5°C), depression of the inshore thermocline (~50 m), anomalous high inshore steric heights (~1.05 dyn. m), anomalous high sea levels (~25 cm), positive subsurface temperature anomalies (3-4°C), negative salinity anomalies (.1-.3 ‰), and positive dissolved oxygen anomalies (0.5-1.5 mℓ/ℓ). The magnitudes of the subsurface anomalies generally are much larger than those of the surface anomalies. The cross-shelf length scales of the subsurface anomalies vary between 300-500 km. During this same period, pronounced negative sea surface temperature anomalies (2-3°C) developed in the central mid-latitude North Pacific. The anomalies, characteristic diagrams, and sign reversals in the salinity and oxygen anomalies are consistent only with enhanced onshore transport of Pacific Subarctic water from the offshore California Current (Simpson, J., GRL, 1984a). The source of this water is primarily from the west-northwest. The subsurface anomalies were produced dynamically by a depression of the inshore thermocline which results from convergence of mass at the coastal boundary. The surface anomalies, however, were produced by a combination of dynamical and local thermodynamical processes. Observed anomalous atmospheric forcing, as reflected in the 700 mb height anomaly and in negative upwelling indices, is consistent with enhanced onshore transport (Simpson, J., GRL, 1983). All the data support the conclusion that the expansion and intensification of the Aleutian Low and decrease in strength of the North Pacific High produced an anomalous basin-wide atmospheric circulation, which coupled directly to the large-scale wind-driven oceanic circulation, to produce the mid-latitude "El Niño" response (Simpson, J., JGR submitted, 1985). Nearly identical mid-latitude atmospheric forcing and oceanic responses were observed during the 1940-41 analog event. A simple model of resonant (El Niño) and anti-resonant (anti-El Niño) wind-induced forcing of the California Current, achieved through enhanced (El Niño) or diminished (anti-El Niño) onshore transport of waters from the West Wind Drift primarily within the latitude band 45-55°N, explains most of the observed warm and cold episodes in the California Current (Simpson, J., GRL, 1984b). This process also explains mid-latitude warm episodes for which there are no corresponding equatorial ENSO events (Simpson, J., Proc. IX Clim. Diag. Workshop, 1985).

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OPTOMA CURRENT MEASUREMENTS

Three deep-sea subsurface moorings were deployed in the OPTOMA (Ocean Prediction Through Observation, Modeling and Analysis) region off Northern California (38°-39°N; 124°-126°W; 3400 m - 4400 m depth). Current meters are at depths 150 m, 350 m, 800 m, 1250 m below the surface and 200 m above the bottom. This observational effort is in conjunction with the OPTOMA modeling and density field (CTD/AXBT) observational programs of A. R. Robinson (Harvard) and C. N. K. Mooers (Naval Postgraduate School). The moorings will be recovered after approximately 9 months deployment in late spring or early summer 1985.

The flow in this region of the California Current System has a strong barotropic component, which is not resolvable with density-field measurements alone. The principal objective for the OPTOMA current meter array is to obtain estimates of the energy in the first few vertical modes. The 100 km separation between moorings should allow some information to be gleaned on eddy/wave propagation.

An implicit additional objective of this observational effort is to obtain an adequate description of the mean and mesoscale flow variability in the California Current System. To this end we will utilize current meter data collected, near 30°N, 127°W during 1979-84, as part of a DOE low level waste disposal program. During 1982-84 these moorings, nearly identical to the OPTOMA moorings, provided data which will allow a comparison of the OPTOMA and DOE measurements to be made and their representativeness to be tested. The initial work on this has begun (Kelley, E. A., M. M. Rienecker, C. N. K. Mooers, and R. L. Smith, EOS, 65:940, 1984. Abstract only).

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Gulf Stream Tomography: A Feasibility Experiment

Ocean acoustic tomography has the promise of providing synoptic measurements of the three dimensional structure of the Gulf Stream, even in the swiftly moving surface layers where sound waves can penetrate along their paths between bottom-mounted instruments. Measurements of mass and heat flux, vorticity (using reciprocal transmission), the ω-$\vec{k}$ spectrum of variability and the sound speed field itself are all candidates to be measured in future tomographic experiments. Tomographic measurements of basin scale variability will depend on measurements in the Gulf Stream. In the proposal we discuss some of the above scientific issues for which we expect to obtain zero-order answers.

A natural sequence of tomographic experiments in the Gulf Stream starts with a feasibility experiment which is proposed here. Acoustic transmissions, centered at 400 Hz and 100 Hz bandwidth between a bottom mounted source and two bottom mounted receivers at 20 km range on either side, will provide much information about the acoustic environment. In the proposed experimental layout, the ray angles at the surface and bottom are much steeper than those in previous tomographic experiments. A preliminary study of the modification to a steeper ray geometry is favorable. The experiment is proposed for the duration of a month in October 1984 near the bottom of the continental slope off Cape Hatteras in a region where the Gulf Stream is usually resident.

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DENSITY, SHEAR AND TURBULENCE MEASUREMENTS IN THE UPPER OCEAN

Temperature, salinity and velocity profile time series were acquired around a 5km box centered on FLIP during MILDEX. The CTD and acoustic doppler current profiler data have been combined to produce density, N^2 and shear Richardson number profiles which map entrainment and stability changes in the mixed layer in the vicinity of FLIP over a ten day period. The gradients of temperature and density across the measurement box are being used to identify large scale features propagating through the area. The spatial distribution of low stability layers are being determined from the Richardson number profiles, and their temporal evolution is being compared with the local atmospheric forcing and the deep inertial wave measurements made from FLIP.

A series of acoustic doppler shear profiles and microstructure measurements were made from the R/S DOLPHIN in conjunction with turbulence measurements made by Tom Osborn during October 1984. Shear profiles with a 1m resolution were measured from the bow of the submarine using a 1.2 M H_z upward-looking acoustic doppler profiler. A concurrent towyo CTD and doppler profiler survey was made from the R/V ACANIA during a period when there was high near-inertial wave activity. The role of the internal wave shear on the observed mixing rates is being examined.

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JAMES H. SWIFT

A STUDY OF THE NORTHERN HEMISPHERE DEEP CIRCULATION

The scientific objectives focus upon the formation and circulation of the deep water masses of the northern hemisphere, with special emphasis upon the Arctic Mediterranean Seas - i.e. the Greenland, Iceland, and Norwegian seas, Arctic Ocean, and peripheral seas. All available hydrographic data are used, but new measurements are undertaken as required to clarify important features and uncover the responsible processes.

Recent results include a re-evaluation of the role of the Arctic Ocean in the global circulation (Aagaard, K., J.H. Swift, and E.C. Carmack, JGR, in press). The previously-held concept was that the deep Arctic Ocean is a passive regime, receiving contributions only from external sources: a "dead-end". But the new results show that the Eurasian sector deep water is an active, responsive regime, which has received recent contributions of "new" deep water from the peripheral shelf seas. This role as a deep water source, rather than sink, makes the Arctic Ocean an effective contributor to the deep layers of the World Ocean.

Geochemical tracer data were used to study the connection between the Greenland Sea and North Atlantic via surface inflow to the Greenland Sea and outflow to the North Atlantic of much denser water masses (Livingston, H.D., J.H. Swift, and H.G. Ostlund, JGR, in press). A tracer signal from European nuclear fuel reprocssing wastes was identified near-bottom south of Denmark Strait only two years after its initial detection in Greenland Sea surface waters, and the identification of the sources for the differing patterns of increase since 1972 of the tracers tritium and cesium-137 provided water mass modification paths and time scales for this system.

A volumetric θ-S census of the Greenland Sea in March-May 1982 has recently been completed. Because this census has been made compatible with a previous tally based upon 1958 data, the new work permits quantitative estimates of the differences between the two years, during an interval when the northern North Atlantic and Greenland, Iceland, and Norwegian seas experienced a major freshening of not only the surface waters, but also the deepest layers.

Other work includes an analysis of the Greenland Sea circulation, combining r cent data sets; tracing new lines of evidence bearing upon the origin of egian Sea Deep Water; an extension of recent North Atlantic analyses (Sw. H., DSR, 1984) southward to 20 S; an examination of new hydrographic da m the Greenland-Spitsbergen Passage (Fram Strait) to determine the or and circulation of the waters; and an examination of the North Pacific deep circulation, using new and historical data.

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GENERAL CIRCULATION

A numerical general circulation model has been developed to investigate the dynamics of recirculation zones analogous to the Gulf Stream and Kuroshio. In addition, a revisit of the classical thermocline theories in light of recent ventilation theories will be done. Although the similarity solutions satisfy somewhat artificial boundary conditions, at present they are the only analytic vehicles available to investigate how deep upwelling, vertical density diffusion, and Ekman pumping produce the characteristic shallow thermocline.

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WARREN B. WHITE

CURRENT RESEARCH: PROCESSES LEADING TO THE DEVELOPMENT OF MESOSCALE VARIABILITY IN THE THERMAL STRUCTURE OF THE KUROSHIO EXTENSION IN THE WESTERN MID-LATITUDE NORTH PACIFIC

During the present year, two studies are proceeding ahead, both in collaboration with other individuals, both funded for the two year period FY85 and FY86. The first study is being conducted in cooperation with Lynne Talley (SIO) and Youhai He (visiting Chinese scholar). It is descriptive/theoretical investigation into the time/space statistical structure and origins of mesoscale variability in the Kuroshio Extension. Two manuscripts are near completion. One manuscript is phenomenological in nature, describing the time/space evolution of mesoscale anomalies in 300 m temperature in the Kuroshio Extension for the 4-year period 1979-1983, establishing that large changes in mesoscale anomaly patterns, on wavelengths of 500-1000 km, occur primarily in winter near bottom bathymetry features. This strongly suggests that mesoscale variability in the Kuroshio Extension is instigated by wind-driven barotropic meridional motion, intensified by bottom bathymetry gradients. The other manuscript is statistical in nature, describing the wavenumber/frequency spectra of mesoscale variability in 300 m temperature in the western mid-latitude North Pacific for the 4 year period 1976-1980, contrasting this with corresponding spectra in the central and eastern mid-latitude ocean. In the central and and eastern mid-latitude ocean, these spectra are shown to have local maxima in spectral energy density located on the dispersion and slowness curves of theoretical baroclinic Rossby waves, the latter modified by the presence of background mean flow. In the western mid-latitude ocean, this is shown not to have been true, with local maxima in spectral energy density occurring at wavelengths and frequency shorter and higher, respectively, than expected for baroclinic Rossby waves. The second study is being conducted in collaboration with Bill Holland (NCAR). It is concerned with the numerical simulation of large-scale and mesoscale anomalies in the mid-latitude North Pacific, for the 8 year period 1977-1984, using a quasi-geostrophic numerical model driven by realistic winds for the period 1965-1985. To date, Bill has built the model on a 1° latitude/longitude grid, employing a realistic coastline and bottom bathymetry. I have provided him with monthly mean-wind stress components based upon 6-hourly wind stress estimates for the 20 years, produced by FNOC in Monterey, CA. We expect that by June 1984, some preliminary simulations will have been made. In the beginning, we plan to test the ability of the model to simulate the statistics of variability in the mid-latitude North Pacific (i.e., the mean, the variance, and covariance matrices of thermocline depth and upper-layer geostrophic flow). If successful with this, then next we shall test the ability of the model to simulate the time/space evolution (i.e., the phase) of variability in these parameters for the 8-year period 1977-1984. Correlation and cross-spectral procedures will be used to determine the percent of observed variance that the model can explain as a function of geographic locations. The model will be interrogated for the dynamical processes responsible for observed variance.

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Robert A. Weller
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THE STRUCTURE AND DYNAMICS OF FLOW WITHIN THE SURFACE MIXED-LAYER

In October and November of 1983 the cooperative Mixed-Layer Dynamics Experiment (MILDEX) was conducted off the coast of California in the vicinity of (34°N, 126°W). As one component of MILDEX, we worked from the Research Platform _FLIP_ in cooperation with Rob Pinkel of Scripps Institution of Oceanography. Horizontal velocity and temperature measurements in the upper 150m of the ocean were obtained using 8 fixed depth and profiling Vector Measuring Current Meters (VMCMs). Horizontal and vertical velocities, conductivity, and temperature were measured with the Real Time Profiler (RTP) in and below the mixed-layer. Meteorological measurements were made from FLIP's mast. In addition, we deployed John Marra's (Lamont-Doherty) fluorometer shackled beneath the RTP.

The objective of this work is to investigate the relation between the observed structure of the velocity and density fields in the upper ocean and local forcing. The period of the MILDEX experiment included both low wind and strong heating conditions and two strong (up to 45 knots) wind events. Measurements of the horizontal velocity and density fields showed that shallow, warm mixed-layers formed when the local heating was strong relative to wind stirring. These diurnal temperature and velocity structures were observed both at _FLIP_ and at the drifting mooring deployed by Oregon State University, as the spatial scales of the solar radiation and surface wind fields were large compared to the separation between _FLIP_ and the drifting mooring. However, the density gradients associated with the diurnal mixed-layers appear to explain only part of the observed vertical shear of the horizontal velocity field found in the upper ocean. There was also shear associated with 24-hour period internal waves and with a mesoscale velocity structure that caused, at times, large differences between the absolute velocity field observed from _FLIP_ and that observed from the Oregon State University drifting mooring.

Using the MILDEX data we seek to understand and model the dynamics of the processes involved in the formation of structures such as diurnal mixed-layers and to investigate the impact of mesoscale variability in the upper ocean on local air-sea interaction processes. We made measurements, for example, in order to find evidence that organized three-dimensional flow was present in the mixed-layer. Such motion might act to efficiently distribute over the entire depth of the mixed layer the momentum and buoyancy input at the air-sea interface. Direct measurements of vertical and horizontal velocities within the mixed-layer in preparation for and during MILDEX did show the presence, on occasion, of strong, organized three-dimensional flows; a description of these observations of Langmuir Cells is in press (Weller, Dean, Marra, Price, Francis, and Boardman, _Science_, 1985).

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HORIZONTAL VARIABILITY IN AIR-SEA INTERACTION

Preparations are underway for a cooperative air-sea interaction experiment planned to investigate the role of horizontal variability in air-sea interaction. The field phase of the experiment will begin in January 1986 and continue to July 1986; the location of the experiment will be the subtropical convergence zone southwest of Bermuda. The cooperative field program includes work both in the upper ocean and in the marine atmospheric boundary layer. Oceanographic measurements will be made from an array of moorings and from ships. Meteorological measurements will be made from surface buoys, ships, and aircraft. Infrared and visible images of the area will be collected by satellite. The objectives of the experiment are: 1) to determine the role of atmospheric forcing in maintaining and modifying the subtropical front over a wide range of space and time scales and to determine to what extent it is necessary to treat the ocean and atmospheric boundary layers as a coupled pair; 2) to determine the magnitude of changes in surface roughness, stress, and drag coefficient across the oceanic front and to investigate the interrelationships between several methods of estimating surface wind stress; 3) to determine the spatial variability of the radiation balance in the vicinity of the front and the impact of front-related clouds on that balance; 4) to determine how the mean structure of the marine atmospheric boundary layer (MABL) and the turbulent fluxes vary across the oceanic front; 5) to investigate the life cycles of turbulent structures in the MABL; 6) to characterize as completely as possible the surface forcing of the upper ocean by the atmosphere in the vicinity of the oceanic front; 7) to describe the three-dimensional velocity, temperature, and conductivity fields in and around the front; and to observe the response of the upper ocean to atmospheric forcing in a domain that spans an oceanic front.

In January 1986 a mooring array consisting of five surface moorings with current meters and meteorological recorders and four subsurface Profiling Current Meter moorings will be set spanning an oceanic front. In February 1986 ships and aircraft will work together making sections perpendicular and parallel to the oceanic front and in the vicinity of the moorings. In June-July 1986 the moorings will be recovered and final surveys made of the area. Overall organization of the cooperative experiment, which has the acronym of FASINEX (Frontal Air-Sea Interaction Experiment), is being done by this investigator and by Steve Stage of Florida State University.

The specific work to be done by this investigator includes the deployment of five surface moorings instrumented with meteorological recorders and current meters; XBT, CTD, and RTP (Real Time Profiler) surveys during the three cruises; and drifting VCM (Vertical Current Meter) deployments. The goals of the field work are to determine the velocity (horizontal and vertical) and density structure of an oceanic front, to investigate the response of the upper ocean to atmospheric forcing, and to determine how the presence of spatial variability such as an oceanic front modifies the response of the upper ocean to atmospheric forcing.

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FERRIS WEBSTER

LARGE-SCALE OCEAN-ATMOSPHERE RESEARCH CO-ORDINATION

The principal investigator is working on the development of a data management system to meet the needs of large-scale oceanographic experiments such as the World Ocean Circulation Experiment (WOCE) and the Interannual Variability of the Tropical Ocean and the Global Atmosphere (TOGA). The launch of oceanographic satellites (NROSS, TOPEX) later in this decade will pose a data-management challenge. Can the large satellite data bases be made widely available so that they can be used with conventional oceanographic data? Activities to date have involved a review of existing activities, the data needs of the research programs, and likely future data handling capabilities. This work has taken place in co-operation with the scientific planning groups for the large-scale research programs.

The next steps will be to determine existing data management activities and data collections in detail, to prepare a data base inventory of these, and to identify future data needs, in collaboration with specialized groups of scientists who will be involved in the experiments. A key step will be to define the characteristics of a data management unit, whose task would be to monitor data originators, analyses, and archives.

A complex data management system to meet the oceanographic needs later in this decade will need to be well tested in advance. One way of beginning this is to prime the pump with historical data. The feasibility of creating a pilot data base will be examined. If feasible, a small data set will be created to serve as a nucleus for further database development and to test procedures for establishing quality control.

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Georges Weatherly

STUDIES OF THE BOTTOM BOUNDARY LAYER AND ABYSSAL FLOWS AS PART OF HEBBLE

The work I am doing stems from my envolvement in the High Energy Benthic Boundary Layer Experiments (HEBBLE) Program. I am analyzing a year-long record of velocity, temperature, and optical transmissivity spanning the bottom boundary layer from 1 m to 200 m above the bottom from the HEBBLE site (40^oN, 62^oW). These data, along with data collected by other HEBBLE investigators, are to be used to validate and further develope combined bottom boundary layer-sediment transport models (e.g., Adams and Weatherly, JGR, 1981). The velocity and temperature data indicate a bottom boundary layer thickness order 45 m thick displaying consistent Ekman layer features such as Ekman veering (about 20^o) and velocity overshoot in the upper portions of the layer. The transmissometer data reveal appreciable re-suspension of bottom sediments during benthic storms (periods of sustained bottom currents of 15 to 40 cm/s). The velocity data and satellite images of the Gulf Stream and rings are being examined to determine possible enfluence of the latter on the benthic storms.

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D. RANDOLPH WATTS

OBSERVATIONS OF THE CURRENT STRUCTURE AND ENERGETICS OF GULF STREAM FLUCTUATIONS DOWNSTREAM OF CAPE HATTERAS

The Gulf Stream leaves the continental margin northeast of Cape Hatteras, NC, and flows into deeper water where meanders propagate and grow downstream. During the past year, we have run a comprehensive field program to study the propagation, growth, internal structure and energetics of Gulf Stream meanders. The work has involved (a) an extensive inverted echo sounder (IES) array (funded at URI jointly by ONR and NSF), (b) a year-long moored array of current meters on five moorings which are centered in the Gulf Stream and extend from the deep ocean to 500 m depth (Co-PI's are R. Watts, URI, and J. Bane, UNC, funded by ONR), and (c) three cruises and nine AXBT surveys. The measurements are expressly designed to test theoretical predictions of barotropic and baroclinic instability.

During the present year (FY85), most of our effort will be directed toward processing and analyzing these data, to prepare appropriate publications.

A Gulf Stream workshop is being held at URI in April 1985 to formulate plans for further theoretical and observational research.

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INTERNAL WAVE TRANSPORT PROCESSES

Principal Investigator: Kenneth M. Watson

Interaction with mesoscale currents is found to provide an effective mechanism for transporting internal wave energy in the $f_e - 2f_e$ band (f_e is the inertial frequency) to high vertical wavenumbers. This mechanism complements the transport mechanisms proposed by McComas, Bretherton, and Müller, which are operative at higher frequencies. The mesoscale interaction is expressed as a diffusion process in internal wave wavenumber space. This assumes a separation of space scales, weak interaction theory, and an ensemble average over specific realizations. Following the model of McComas et al, phenomenological energy input is assumed at low vertical wavenumbers and dissipation at high vertical wavenumbers. A quasi-steady state internal wave spectrum is calculated. This is similar to that proposed by Garrett and Munk. Energy input to the internal wave field from mesoscale currents is predicted to be $\cong 4 \times 10^{-3}$ W/m^2 for an rms current of 10 cm/sec. Horizontal and vertial eddy viscosities are predicted to be 40 and 5×10^{-3} m^2/sec, respectively. A Richardson number of 1/7 is also calculated. Dissipation and energy input are predicted to scale with mesocale energy, but the internal wave energy level appears to be rather insensitive to this.

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PERSISTENCE OF SURFACE WAVE PATTERNS

Principal Investigator: Kenneth M. Watson

The observation of ship Kelvin wakes by the Seasat SAR raises a question concerning the persistence of patterns of surface gravity waves. Time scales vary with wavelength and environmental conditions. The range extends from fractions of a second at the shortest wavelengths to many days for ocean swell. Several mechanisms for destroying a wave pattern are investigated here. These are viscous dissipation, direct wind-wave interaction, and nonlinear hydrodynamic interaction with ambient surface waves. The nonlinear hydrodynamic interactions appear to be the most significant.

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Expanded Study of the Inverse Problem for Ocean Circulation

George Veronis
Manuel Fiadeiro

Hydrographic data, CTD's, and chemical tracer distributions are obtained mainly for the purpose of determining the (large or small scale) circulation of the oceans. The analysis of these data requires a conceptual framework for interpreting the distributions. Though such a framework is often intuitive, it can usually be formulated quantitatively in which case it falls into the class known as inverse problems. Inverse theory provides a rigorous methodology for analyzing the data and allows one to determine what kind of information is accessible from a given data set.

Our present research falls into two categories. The first is the development of reliable and reproducible inverse procedures for determining ocean circulation from hydrographic data (Fiadeiro and Veronis, JMR, 1982; JPO, 1983; Veronis, Scripps Lectures 1983 (publ. 1985)) and from tracer data (Fiadeiro and Veronis, JPO, 1985). The second is the application of these procedures to observed data sets (first three articles cited). We are currently analyzing two data sets; one is in the beta-triangle region (Armi and Stommel, 1983) and the other is from JASIN. The latter is particularly well-suited for inverse analyses based on hydrography and on tracers. Current theoretical studies focus on the possible determination of mixing coefficients as well as velocities from tracer distributions. A complete determination of variable mixing coefficients is not feasible with the kind of oceanographic data likely to be available. The emphasis, therefore, is on the approximate information that can be obtained.

Because of the paucity of suitable oceanographic data, a collaborative effort is under way to test theoretical findings with coastal and river data gathered by a group in Western Australia. Field observations and data analyses are carried out by that group. We have provided the theoretical basis and a critical overview of the methodology.

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JOHN M. TOOLE

HYDROGRAPHIC OBSERVATIONS IN THE AGULHAS RETROFLECTION AREA

The Agulhas current, one of the world's major western boundary currents, typically exhibits a sharp reversal south of the African continent. This behavior has been termed the Agulhas retroflection. Our understanding of this phenomena is deficient at present but modeling efforts are underway: exploring wind and buoyancy driving as causes for the reversal (de Ruijeter and Boudra, 1984, unpublished manuscript; Luyten and Stommel, 1985, unpublished manuscript). This month a current meter array will be deployed in the retroflection area by J. Luyten to study the vertical structure and temporal evolution of the flow. The present contract supports hydrographic (temperature, salinity, dissolved oxygen) sampling during that cruise. The station plan calls for several transects across the flow axis of the Agulhas as well as sampling within the warm water pool enclosed by the current loop. The goals of the program are to document the downstream variation in the current structure (volume transport, potential vorticity, ...), classify the water mass characteristics of the waters inside and out of the retroflection eddy and assess the effects of winter cooling on the water column, and to search for evidence of net transport of Indian Ocean water into the South Atlantic. The cruise is scheduled for February 20 through March 28, 1985.

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EUGENE A. TERRAY

MEASUREMENT OF TURBULENCE BENEATH WIND WAVES USING COHERENT DOPPLER SCATTERING

We are developing a three-axis, range-gated, Coherent Doppler Sonar (CODS) to measure the vertical structure and statistical characteristics of small-scale turbulence in the upper mixed layer. Our goal is to determine the turbulent fluxes of energy and momentum driven by the local wind stress, and to assess the relative importance of production, transport and dissipation in establishing the observed turbulence distribution, with particular attention to the influence of the surface wave field.

During the first year, we are building a three-axis, multi-range, prototype instrument, and have begun simulation studies to determine the signal processing requirements. Work is also underway to use frequency multiplexing to reduce the level of Doppler noise. In year two, we will extend the range of the device by means of pulse coding, and deploy it from a fixed tower for field testing.

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LYNNE D. TALLEY

MESOSCALE VARIABILITY AND INSTABILITIES OF THE KUROSHIO EXTENSION

The primary source of eddy variability in the western North Pacific Ocean is the Kuroshio Extension, undoubtedly through its instabilities. The principal objectives of the research are (1) to describe the nature of variability in the western Pacific, using the Transpac XBT data as a primary data source, (2) to extend a theoretical model of linear instabilities to finite amplitude and to more complicated flows which better correspond with the mean structure of the Kuroshio Extension, and (3) to examine the growth of such instabilities in numerical models. The instabilities mentioned in the second and third objectives can be trapped to the Kuroshio Extension or can radiate energy far north and south of the Current. Very little is known about radiating instabilities (which depend on the existence of Rossby waves in the ocean north and south of the current) and the latter two objectives are focused entirely on understanding them.

Warren White and I have been analyzing the Transpac XBT data in the mid-latitude North Pacific. We have found that the wavenumber and frequency spectra vary from the western to the eastern Pacific. The spectra are generally consistent with Rossby wave propagation in a slow, mean, eastward flow. We have found that the wind field, which can account for forcing of the spectra in the eastern Pacific, cannot account for the spectra in the western Pacific. The spectrum in the western Pacific is assumed to arise from instability of the Kuroshio Extension. Time and space sampling in the data set in the western Pacific is unfortunately not adequate to estimate energy transfers so we are turning to other data sources to better determine the role of instability of the Kuroshio Extension.

Radiating instabilities have been examined in barotropic and baroclinic models of currents like the Kuroshio Extension (Talley, J.P.O., 1983). I have nearly completed an analytical, nonlinear extension of the barotropic instability calculation: the goal is to determine the structure of radiating instabilities in the ocean interior, north and south of the current. I will be collaborating with Dale Haidvogel beginning in March, 1985, to determine the evolution of radiating instability in numerical models where the range of mean flows and parameters which can be explored is much greater than is accessible in analytical models.

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JAMES H. SWIFT

HYDROGRAPHIC SAMPLING DURING AIWEX

This research project is one component of the Arctic Internal Waves Experiment, a multi-institution study of the internal wave field and mesoscale features in the Canadian Basin of the Arctic Ocean. The experiment is to be carried out ca. 220 nmiles north of Prudhoe Bay during March-April 1985. The hydrographic measurements program will return the absolute values and vertical gradients of temperature, salinity, oxygen, and "nutrients" from the surface to the bottom at the site. Additionally, the intermediate and deep water layers at the site will be examined both for evidence of variability over a one-month period and also for evidence of winter-derived contributions which have spread laterally from the peripheral shelf seas. Also included is the collection of geochemical samples (tritium, helium-3, cesium-137, and strontium-90) for return to laboratories ashore.

The hydrographic measurements support other AIWEX programs by providing water column data for calibration and for referencing smaller-scale features. This program will also prpvide a unique Canadian Basin deep water data set to address issues related to the basic structure of the water column. The expected measurement confidence will permit direct comparisons with recent data sets from the Arctic Ocean and other regions. Finally, the AIWEX hydrographic work will establish an operational baseline: the program deliberately uses a minimum of personnel and equipment in order to provide a bottom-line estimate for future ice-camp hydrographic operations.

One Scripps technician will support the hydrographic measurements program on the ice for 4 weeks, with help from a second person during the first week of construction and testing. All analyses for temperature, salinity, oxygen, and nutrients will be completed on the ice, in a small temperature-controlled laboratory installed inside an Arctic field tent. A second tent will cover the hydrohole and contain the wet lab equipment. In addition to the hydrographic and tracer measurements, a self-contained conductivity/temperature/pressure instrument will be lowered to the bottom, and daily depth soundings will be made.

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Norman J. Zabusky

EVOLVING NONLINEAR JETS AND RINGS AND MODELS OF GULF STREAM VARIABILITY

The work in collaboration with G. Flierl and P.M. Rizzoli on evolving jets on the beta plane was reported to the American Physical Society Division of Fluid Dynamics (November 1985). At this time, ideas were generated for a continuing study of the nonlinear stability of isolated eddies and rings with finite beta and gamma (i.e., inverse deformation radius). This work was formalized in a letter of December 1984 to G. Flier from N. Zabusky and N. Mélander.

The work with J. McWilliams was continued and a manuscript on the axisymmetrization process was exchanged. Here we have given a kinematic description of axisymmetrization using saddle points and critical contours of the stream function in a corotating reference frame. In a manuscript in preparation we have used an elliptically desingularized vortex model to analyze the convective merger of two identical vortices via a phase plane description. This is the first time that an analytical description of the oft-observed merger phenomenon has been given!

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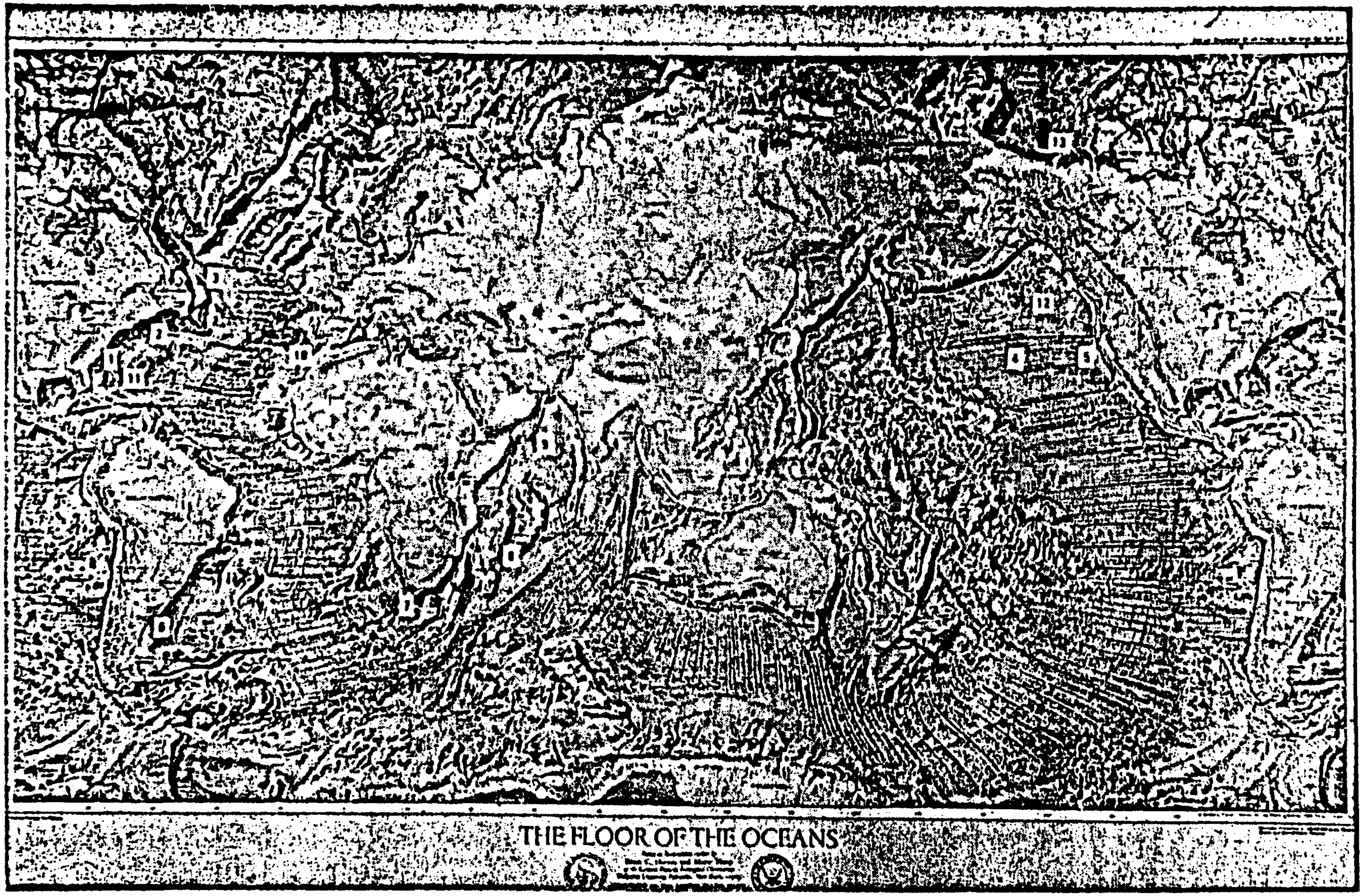
THE FLOOR OF THE OCEANS

FY86-FY87 FIELD PROGRAMS

KEY/LOCATION	PROJECT	PRINCIPAL INVESTIGATORS
A. LARGE/MESO SCALE PROCESSES		
1. Western North Atlantic	Gulf Stream System	Bane, Levine, Malanotte-Rizzoli, Rossby, Spiesberger, Watts
2. New England Seamounts	Eddy-Mean Interactions	Hogg, Rossby
3. Newfoundland Basin	SOFAR Eddy Dynamics	Owens
4. Eastern North Pacific	Thermocline Dynamics	Keffer, Niiler
5. California Current	OPTOMA, Frontal Studies	Armi, Cox, Mooers, Robinson, Smith
6. Brazil-Argentina	Brazil-Falkland Currents	Brown, Evans, Garzoli, Gordon Olson, McCartney, Roden
7. Agulhas-Benguela	Retroflection	Brown, Fine, Luyten, Olson, Toole
8. Southwest Indian	Boundary Currents	Fine, Schott
9. Arabian Sea, NW Indian	Deep Circulation	Warren
10. Gibraltar	Outflow Studies	Lueck, Price, Sanford, Weiss
B. SMALL SCALE PROCESSES		
5. California	PATCHEX: Mixing Dynamics	Briscoe, Gregg, NRL, Pinkel
11. S. of West Bermuda	FASINEX - Frontal Air/Sea Interaction Experiment	Weller, Stage, 11 Other ONR PI's, 4 other U.S. Agencies
12. NE Pacific	OCEAN STORMS - Air/Sea: Strong Forcing	d'Asaro, Richman, 13 other ONR PI's, 4 other U.S. and 2 Canadian Agencies
13. Beaufort Sea	AIWEX: Arctic Internal Wave Experiment	d'Asaro, Dillon, Levine, Paulson Pinkel, Swift

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